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# Journal of Sedimentary Petrology

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A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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# Journal of Sedimentary Petrology

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 53–63, AUGUST, 1941

# THE FRONTIERS OF SEDIMENTARY MINERALOGY AND PETROLOGY*

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## ABSTRACT

The frontiers of sedimentary mineralogy and petrology are defined as the boundaries separating the known from the unknown. Evaluation of the usefulness of several techniques for advancing the boundaries into the unknown is presented and several problems of the West Gulf Coast and Midcontinent regions are suggested as places where the unknown invites exploration.

## INTRODUCTION

The frontiers of sedimentary mineralogy and petrology are marked by an imaginary line that separates what is known from the unknown. The known represents the territory invaded by the advance into, or the colonization of this field of knowledge. As in any colonization there are places where advance was made too rapidly, where hopes were raised too high; the advance was made without adequate support of knowledge already learned. It would be strange, indeed, if in the development of sedimentary mineralogy and petrology some of these things had not taken place.

Sedimentary mineralogy and petrology have made great advances during the past quarter of a century, but the whole world was the field of study. The frontiers separating the known from the unknown show only a small part of the great territory under the control of what is known, thus leaving a vast expanse subject to future discovery and investigation.

Sedimentary minerals are of authigenic and allogenic origin, the former originating with and in the sediments of which they are a part, the latter originating in other rocks and becoming incorporated after some transportation in the sediments with which they are associated. Sedimentary rocks are made from the two kinds of minerals.

* This is one of two papers directed to be prepared by the Research Committee of the Society of Economic Paleontologists and Mineralogists. The other paper is by Doctor M. A. Hanna. It will be published in the Journal of Paleontology.

The authigenic minerals are reactions to the environmental conditions existing at the times and places where the sediments of which they are a part were deposited, or to conditions that existed in the soft sediments after deposition. Allogenic minerals reflect conditions present at the time of formation of the rocks of which these minerals were once a part. They bear little or no relation to the environmental conditions prevailing at the time of formation of the sediments into which they enter, but some marks may be impressed upon them by the agents by which they were transported and deposited. Allogenic minerals may direct one to the parent rocks in which they were once included. These are termed the distributive rocks or provenances. They may also tell something of the conditions which brought about release from the parent rocks.

Allogenic minerals may be placed in three classes of stable, metastable, and unstable. These terms relate to the resistances of the minerals to the processes that lead to their destruction. Resistance depends on a number of factors of which solubility, decomposition, toughness, cleavability, and hardness are important. Minerals that have a high degree of insolubility, do not decompose readily, are tough and hard, and are very stable. Minerals that are soluble in natural waters, decompose easily, and are brittle and soft are very unstable and easily destroyed. Most minerals hold some intermediate position. Some minerals are weak from the point of view of decomposibility, but are hard, tough, and rela-

tively insoluble. Such is pyrite. Others are soluble, but are difficultly decomposed under natural conditions as is the case for calcite. A stable mineral possesses all resistant properties to a high degree. Metastable minerals are those having intermediate properties of resistance, or intermediate resistance in some of the properties. Examples are the feldspars. Unstable minerals are those that are weak in one or more of the properties that produce resistance. Calcite and dolomite are such minerals.

Separation of allogenes from authigenes is not always easy as it has been learned that many minerals previously considered characteristic of igneous and metamorphic rocks may also be formed in sedimentary rocks under normal sedimentary conditions. Allogenes have undergone some transportation previous to their deposition with other sediments and they hence should exhibit some wear. They may have been broken on release from some pre-existing rocks and they should show some evidence of this fact. Authigenes, on the other hand, form within or with the sediments of which they are parts. They should have crystal form to some degree and should not exhibit abrasion.

Many sediments contain particles of which the central part is allogenic, the outer part authigenic. The authigenic part may or may not be in crystal continuity with the central part, and it may not be composed of the same substance. The particle may, but need not have crystal outlines. The internal part may contain evidence of the conditions existing at the place where the parent rock was destroyed, the external part of the conditions prevailing at the place of deposition.

## MECHANICAL ANALYSES

Mechanical analyses of sediments are made to determine the approximate dimensional compositions of the composing materials. The analyses also show the degree of sorting. Analyses are usually made according to the Wentworth grade scale. Particles with dimensions greater than 1/16 mm. are separated by means of sieves. Separation of particles with dimensions below 1/16 mm. is usually done by some method of subsidation or elutriation into silt- and clay-size fractions or some division of these grades. The best methods of fractioning the fine-grained particles are considered to be the pipette method of Krumbein or the hydrometer-pipette method of Hellman and McKelvey. Much has been claimed for the Bouyoucos hydrometer method and this seems to be reliable for some sediments. Either of the methods may be used to separate the clay- and silt-size grades into fractions, but it is thought that this will not accomplish anything of sedimentary significance, particularly if the sediments have been deposited for any great length of time. Small particles are readily transported by currents of almost negligible turbulence and competence, they settle very largely by flocculation, they may make many passages through the elementary tracts of animals, they may undergo diagenetic changes after deposition, they must be deflocculated before analysis, and after the results of analysis have been obtained one must peer through the deflocculation, the diagenetic changes that took place during and after deposition, the passages through intestinal tracts, and the flocculation that produced deposition in order to arrive at the original dimensions of the particles. *This just can not be done.* Analysis of the fine-grained particles may be useful and desirable for showing the dimensions of particles after deflocculation, but it may show little, if anything, of the states and dimensions of the particles when they were in suspension. The bentonite beds in the Cretaceous of the Rocky Mountains and Great Plains regions were deposited as volcanic ash. The deposits are now largely composed of clay minerals. Analysis of these clay-size particles will show nothing of sedimentational significance so far as the dimensions of the particles at the times of deposition are concerned. The analysis, however, may be of service for industrial uses.

### SIGNIFICANCE OF MINERAL QUANTITY

Determination of mineral quantity may be done in one of several ways, but the method in common use is that by means of heavy liquids. The method may be learned by consultation of the *Manual of Sedimentary Petrography* by Krumbein and Pettijohn, and *Methods of Study of Sediments* by Twenhofel and Tyler. Determination of quantity may be done by actual weighing of mineral particles after their separation has been made, or by counting particles under a microscope equipped with a mechanical stage or some other device by which the number of particles of different minerals on a slide may be counted. Determination of quantity by weighing is far more accurate, but reasonable accuracy by counting may be attained if a sediment is first separated into fractions, the weights of the fractions determined, the counts made for each fraction, and finally the total percentage of each mineral determined by means of a summation of the percentages of each mineral per fraction.

Correlations have been made on the basis of the percentages of certain minerals in a sediment. It is thought that in some cases these percentages may be useful in correlation, but the exceptions are considered to be almost, if not more numerous, than the cases in which this tool may be applied. The method of correlation is thus considered too fraught with error to justify its use. Sediments of some existing sea shores and the adjacent shallow water may contain such minerals as garnet, magnetite or ilmenite with range from almost zero to over 50 per cent with the extremes only a few rods distant from each other.

### SIGNIFICANCE OF GRAPHS OF MECHANICAL ANALYSES OF SEDIMENTS

Graphs of the mechanical analyses of sediments show positions in the grade scale, the degree of sorting, and the shapes of the curves or other diagrams produced by size frequencies. These characters may be seen in illustrations in the publications of Udden, Goldman, Krumbein and others. Much has been claimed for what may be accomplished with graphs. It has been stated (Tanner, 1939) that the environment and agents of deposition may be identified from graphs or histograms. *This most certainly can not be done.* The best that a graph can do is to suggest a possible environment of deposition and a possible agent of deposition. Sediments deposited in several environments may have identical graphs. Other characters of sediments as shape, rounding, dimensional range of rounding, surface markings on particles, associations with other sediments, sedimentary structural features, etc. may prove the environment and agent of deposition, but certainly the shapes of the graphs can not do so.

Correlations have also been based on graphs of mechanical analyses. Such correlations are very dangerous. The writer has made analyses of sands ranging from the Cambrian system to those on modern sea shores and if correlations based on the shapes of graphs were valid it would be easy to prove that a Cambrian sand correlates with some sand from every geologic system. This method of correlation has a very limited local application. Most other methods of correlation are much better.

### SIGNIFICANCE OF DISTINCTIVE MINERALS OR MINERALS WITH DISTINCTIVE CHARACTERISTICS

Many allogenic minerals are very characteristic of the parent rocks from which they were derived, either because of being a very distinctive variety, or because of possessing distinctive features such as structures and textures produced by metamorphism, pressure effects, or optical properties. Careful observations of igneous and metamorphic rocks, the potential parents of sediments, can hardly fail to show the presence of distinctive minerals, or minerals with distinctive features. Thus, there are several varieties of zircon, several varieties of tourmaline, and others. These varieties should be

recognized and their properties described. The day should be past when it is considered sufficient to state that rocks contain zircon, tourmaline, or any other mineral. It is necessary to state the kinds of zircon, or other mineral, and the optical properties that the variety or varieties possess. Zircons from a half dozen sources with as many different properties may be present in a sediment and merely be identified as zircon. *Parent rocks can not be positively identified on such data.* The variety or varieties must be identified and their optical properties determined. The sources are then possible of determination. This can not be done on general identifications. A work showing application of this principle is that of Grout and Thiel and Tyler and Marsden (1940) on the Pre-Cambrian igneous and sedimentary rocks of the Lake Superior region.

Many allogenic minerals contain inclusions of other minerals, particularly allogenes derived from igneous rocks or metamorphic rocks of igneous parentage. These inclusions may more eloquently indicate the parent rocks than the allogenic particles in which they are contained, as the protection afforded by the containing allogenic particles preserves an association of minerals ranging from very unstable to very stable. This association renders it easy to recognize the parent rock as like minerals therein should contain the same inclusions as the allogenic particles.

The first stratigraphic appearance in sediments of distinctive minerals, or minerals with distinctive properties, fixes the times that the source rocks were in position to yield sediments to the sites of deposition represented by the sediments. The introduction of these minerals was due either to removal of cover from the source rocks, or they were placed in positions which enabled them to yield sediments. Thus the new minerals date an important geologic event. Their entrance into the sediments also permits some degree of correlation. However, one can rarely be certain that entrance into the sediments of these minerals was synchronous in all marginal localities and in most instances this would not be the case.

The presence of identical distinctive minerals, or minerals with distinctive properties in different occurrences of igneous and metamorphic rocks may be taken as indicating that the rocks containing these minerals have a common origin and similar time relationships. This generally makes it possible to correlate igneous terranes that have no apparent connections with each other and whose age relations can not be determined from associated sediments. Such correlation may even be made in magmatic differentiates that may not closely resemble each other but do contain the same distinctive mineral suites. This has been done with reasonable success by Grout and Thiel in Minnesota and Tyler and Marsden in Wisconsin for the Pre-Cambrian rocks of the upper Mississippi Valley.

Unstable allogenic minerals of igneous origin in sedimentary terranes do not certainly prove that an igneous rock was the immediate parent. The parent rock may have been an arkose or a graywacke. If all allogenic minerals in a sedimentary formation are of stable character, it is very strongly suggested that the immediate parent was a sedimentary terrane. This, however, is not proven as very mature decomposition may completely eliminate all unstable and metastable minerals and leave only decomposition products and stable minerals. Caution is hence essential. A sedimentary rock having a parent like the Newark sandstones of the Connecticut River Valley may contain almost as many particles of unstable minerals as another sedimentary formation having a granite for the immediate parent. The Baraboo quartzite, a pre-Cambrian formation of southern Wisconsin, consists of over 99 per cent of particles of quartz. There are some particles of zircon, an occasional one of tourmaline, a rare particle of garnet, and some authigenic substances. It seems likely that the immediate parent or parents of this for-

mation were sedimentary and the unstable and metastable minerals had been eliminated in at least two cycles of destruction and deposition.

### APPLICATIONS OF SEDIMENTARY MINERALOGY AND PETROGRAPHY

The foregoing paragraphs have presented general principles. Some of the tools of sedimentary mineralogy and petrography have been described, their limitations have been stated, and their possible uses have been suggested. Sedimentary mineralogy and petrography may serve to assist in finding mineral resources either by aiding to decipher the local geological conditions, or by directing discovery to source rocks from which commercially important allogenic minerals were derived; to aid in determining the geologic history involved in the formation of any sedimentary deposit; and, to assist in an understanding of the paleogeography of the region in which the sediments were deposited and that of the region from which the allogenic minerals were derived.

With the background outlined in preceding paragraphs, it is pertinent to inquire how a program may be adopted which may be expected to advance the frontiers of sedimentary mineralogy and petrography. It is also pertinent to inquire if the advance of these fields of knowledge has been uniform to date, or if there have been salients in the advance. The writer believes there are such salients. Much has been made of mechanical analyses and values derived from them for correlative and comparative purposes and also for determination of the environments of deposition. There is no question of the value for comparative purposes and there is no known better method for comparison of sediments than the several different forms of diagrammatic representation that have been devised. Much has also been made of mineral frequencies, but it is the writer's judgment that these have little value beyond giving detail respecting the quantities of minerals present. It is believed that they should not be given much weight for use in correlation. The kinds of minerals, whether allogenic or authigenic, give information which has geologic significance. Detailed and distinctive characters of minerals, such as strain shadows, inclusions and particular characteristics of minerals represent a somewhat neglected field. This field is of the nature of a bay in the frontier of research in sedimentary mineralogy between the two salients of mechanical analysis of sediments and mineral frequencies, and it is the writer's opinion that this bay is a place on the frontier of study of minerals of sediments where research may be extremely fruitful of results. There are many places where this bay may be explored. A few are considered.

### DISTRIBUTION OF MINERALS IN SEDIMENTS

Cogen (1940) and others have investigated the distribution of allogenic minerals in the Gulf Coast section and on the bottom of the Gulf of Mexico off the coast of Texas and Louisiana and it has been shown that distribution has regional and stratigraphic variations. Bornhauser (1941) has studied the distribution of several allogenic minerals in the West Gulf Coast sediments and has concluded that there have been contributions from two general regions and that these have two separate distributions of which one is the Rio Grande and the other the Mississippi embayment. None of the writers has directed the reader to the source rocks or areas. Sidwell (1930, 1940) of the Texas Technological College of Lubbock, Texas, has studied the distribution of sediments in the deposits of some rivers of West Texas and the contributions made by certain terranes. These writers used certain common minerals but beyond giving a general name to each mineral and the colors of some of them, none has gone into, or even determined, the varietal differences in physical and optical properties to make it possible for their

readers to know the nature of the varietal differences.

### THE CENTRAL MINERAL REGION OF TEXAS AND BORDERING SEDIMENTARY ROCKS

The Central Mineral Region or Dome of Texas has a core of igneous and metamorphic rocks. The latter are known as the Spring Valley gneiss and Packsaddle schist. The igneous rocks are largely granites. These igneous and metamorphic rocks have been studied and the general petrography of some terranes is known (McAdams, 1936), but the writer is not aware that any studies like those made by Grout and Thiel and Tyler and Marsden in the Pre-Cambrian of the upper Mississippi Valley have been made to find particular varieties of minerals with determinable optical properties, minerals with particular distinctive characteristics, or with particular inclusions or suites of inclusions. Some of these are quite certain to be present and one may quite confidently predict their finding. It should be determined whether each igneous and metamorphic terrane carries distinctive minerals or minerals with distinctive characteristics. At some time in the past the rocks of the Central Mineral Region were covered by Pre-Cambrian sedimentary rocks and at some later date, but before the Upper Cambrian, the sedimentary cover was removed by erosion and the igneous and metamorphic rocks were exposed and eroded. The distinctive minerals should then have entered the sediments and they should be present in the upper Cambrian sandstones which are exposed around the margins of the Central Mineral Region. It is not known that any careful search has been made in the bordering sediments for distinctive minerals that might be traced to the igneous and metamorphic rocks. The region seems to have been covered for sometime in the Ordovician and again in the Pennsylvanian and there was deposited a sedimentary cover consisting of Ordovician and Pennsylvanian rocks. There was erosion of the region at times during the Paleozoic, but it does not seem likely that the igneous and metamorphic rocks were exposed. The region was raised after the Pennsylvanian and the entire cover of Paleozoic strata was removed after which distinctive minerals derived from the igneous and metamorphic rocks should have entered the sediments. These should be found in the basal Cretaceous strata. The Cretaceous seas entirely surrounded the region and ultimately extended entirely over it and the igneous and metamorphic rocks were then covered a third time. Emergence after the Cretaceous again stripped off the cover and for the third time the rocks of the core of the Central Mineral Region were in a position to yield distinctive minerals to the sediments. These should have entered the Tertiary sediments at a definite time following the unroofing and the first appearance of these minerals would indicate the approximate date of the unroofing.

There are other angles to the problem. The distribution of any distinctive mineral in the vicinity of the Central Mineral Region should show radial directions of travel. The sites of deposition in the Tertiary should be eastward and southeastward downstream to the sea and along the shores of the sea northeast, southwest, or both directions from the places of stream entrance into the sea. The two different media of aqueous travel would be indicated by the nature of the deposits in which the distinctive minerals are found, those of stream deposition in continental deposits, those of marine deposition in shallow marine water deposits and along the shores of the sea, in the first case radial to the Central Mineral Region and in the second case in some degree tangential to the Central Mineral Region. Study of the mineral distribution in the continental deposits might lead to determination of the directions and shiftings of the drainage since the unroofing of the granites, gneisses and schists of the Central Mineral Region.

Once the distinctive minerals of the

Central Mineral Region are accurately known, it should be easy to determine contributions of allogenic minerals from terranes of other regions as these would be likely to have different characteristics. Thus advance would be made in an understanding of some paleogeography of the west Gulf Coast Region.

None of this work seems to have been done. The presence of distinctive minerals in the igneous and metamorphic rocks of the Central Mineral Region remains to be determined. Very little seems to be known of distribution of allogenic minerals derived from the Central Mineral Region in the sedimentary rocks which surround it. Minerals have been recognized in the sediments but they have been broadly identified as zircon, olivine, hornblende, etc. The identifications should be in more detail and attempts should be made to learn the extent to which the Central Mineral Region has served as a distributive area. Perhaps it had little part in formation of Gulf Coast sediments.

The Central Mineral Region was also a possible distributive area for the Cretaceous sediments to the west. The buried land area of east Texas or Llanoria is probably responsible for some of the sediments which formed the Pennsylvanian and Permian strata of North Central Texas and still later for some of the sediments in the basal Cretaceous on the west side of the Central Mineral Region. If this was the case it should be possible to determine the presence of distinctive minerals derived from the rocks of the Central Mineral Region in the sediments of the Cretaceous strata. Such studies do not seem to have been made.

### THE OUACHITA BASIN AND LLANORIA

In southeastern Oklahoma and adjacent Arkansas and more or less under cover in adjacent Louisiana and Texas is a great thickness of Pennsylvanian and older sediments which have been said by Miser (1921) and others, to have been deposited in the Ouachita Basin or geosyncline and to have been derived from Llanoria, a postulated upland region now buried beneath the Cretaceous and Tertiary strata of the West Gulf Coastal Plain. The Central Mineral Region has been considered a western outpost of Llanoria. The existence of this upland in the sense postulated by Miser has been questioned by van der Gracht (1931) who assumes "a great chain of mountains, consisting of an outer zone of old-Paleozoics in Ouachita facies, succeeded farther back by crystalline, metamorphic and granitic rocks of the more central, and presumable older ranges, or incorporated ancient massifs." These sediments have been stated to thicken to the south and also to become coarser in that direction, thus suggesting a source to the south. It is probable that a comparative study of the minerals of the sedimentary rocks in the Ouachita Basin or geosyncline and the igneous and metamorphic rocks which the drill has found beneath the Cretaceous sediments would very definitely show whether or not the postulated Llanoria was a provenance for the sediments. Samples of these ancient rocks have been acquired from wells drilled to them and they are excellently exposed in the Central Mineral Region. Minerals of distinctive variety might be recognized in the Central Mineral Region, but that region is a considerable distance from the sites of deposition in the Ouachita Basin and it may be that it was not in position to make additions to the sediments brought to that site of deposition. Perhaps the samples of the igneous rocks encountered beneath the Cretaceous and Tertiary sediments were in too small quantities to yield distinctive minerals. Perhaps the samples have been lost and it may not be possible at this time to determine whether these ancient rocks were a provenance for sediments deposited in the Ouachita Basin. The importance of information on this subject should be a spur to rouse interest and when deep wells are drilled, attempts should be made to recover samples of the ancient rocks of the postulated Llanoria.

Studies of the sediments in the Ouach-

ita Basin would most certainly yield information as to whether or not they contain distinctive minerals, in which units these are present, the character of distribution in those units, and whether they are the same in every unit. After this information has been found, the next step in the research is a search of all possible sources other than Llanoria in order to see if these might contribute the distinctive minerals, even if the possibilities of these rocks as provenances may be remote. Possibly sources are the Colbert porphyry and the Tishomingo granite of the Arbuckle Mountains. Other sources are the igneous rocks exposed in the Wichita Mountains and in Arkansas. Exposures in each of these three places are good and determination of the presence of distinctive minerals should not be difficult. If the same distinctive minerals are found in the sediments as in some of the igneous rocks the hypothesis that these rocks formed sources for some of the sediments may be entertained. It is expected that it will be found that allogenic minerals of the sedimentary rocks are unlike those of the igneous rocks of the three regions named and that the igneous rocks of Oklahoma and Arkansas have no or very little responsibility for the sediments deposited in the Ouachita Basin.

However, the igneous rocks of Oklahoma and Arkansas yielded sediments that must have entered the Tertiary and Cretaceous strata of Louisiana, Arkansas, Oklahoma and Texas. It should be possible to determine the extent to which this was done by studies of distinctive minerals in those strata of Wichita, Arbuckle, or Ouachita provenances. The times of appearance of these minerals in the geologic section mark events of considerable significance to the geologic history of the region and they may have some commercial importance.

### THE "RED BEDS" OF KANSAS AND OKLAHOMA

The sources of the sediments that form the "Red Beds" of Kansas and Oklahoma have not been definitely determined. Perhaps there are several. Possible source areas for parts of the "Red Beds" are the Wichita and Arbuckle mountains of Oklahoma, remotely perhaps the upland areas of Arkansas, and, more probably, uplands in the region of the present Rocky Mountains. The possible provenances should be studied for distinctive minerals and these with their optical and other characteristics should be described and the descriptions published. It would then be easy to determine the extent to which the igneous rocks of the regions named were important sources for the sediments of the "Red Beds." It is suspected that it will be found that the region of the present Rocky Mountains was the chief distributive area.

### THE ST. FRANCIS MOUNTAINS OF MISSOURI

The St. Francis Mountains in southeastern Missouri represent an ancient Pre-Cambrian area that was buried beneath late Cambrian and early Ordovician sediments. The composing rocks are crystallines. These rocks should possess distinctive minerals and these should have distribution in the margining upper Cambrian and basal Ordovician sediments. It is not known that such distribution has been found.

### NEMAHA NOUNTAINS OF KANSAS

The Nemaha Mountains are a buried range of mountains which crosses east-central Kansas from northeast to southwest. They were buried beneath Pennsylvanian strata. This range of mountains was made known by drilling and a considerable number of fragments of igneous and metamorphic rocks have been brought to the surface during the past 25 years. Any fragments which are still in existence should be studied for distinctive minerals. Also many samples of the sedimentary rocks have been acquired by drilling about the margins of these buried mountains. Some correlation by means of minerals should be possible.

### AMARILLO MOUNTAINS OF WESTERN OKLAHOMA

The Amarillo Mountains of western Oklahoma represent a range of mountains that are like, and a continuation of, the Wichita Mountains of southern Oklahoma. They have not yet been exhumed. Samples of the rocks of these mountains must have been acquired by the drilling in that region and some correlation should be possible between minerals of the bordering sediments and those of the rocks of the mountains.

### SUMMARY

The above paragraphs in rather broad outlines present a few of the problems that are awaiting attack in the field of allogenic sedimentary mineralogy and which offer hope of fruitful results. More or less parallel studies of rocks of distributive areas and the sediments supposed to be derived from them should be made. The times of covering and uncovering of source areas may thus be determined. In some cases results will, no doubt, be inconclusive. This, however, is inevitable. In all research of allogenic sedimentary minerals optical properties should be given in detail.

### AUTHIGENIC MINERALS

There are many authigenic minerals of which little is known. Nearly every marine limestone which has been studied has yielded feldspars of sedimentary origin. It has been suggested by Crowley (1939) that sedimentary feldspars do not form in freshwater sediments. This may be the case, but it can only be established by more research than has yet been done. It has also been suggested that sedimentary feldspars are particularly common in limestones which to a considerable degree are of algal origin (de Lapparent, 1918). Neither of these suggestions has received much study and it may be very positively stated that essentially nothing is known respecting the conditions that are responsible for the formation of feldspar of sedimentary origin. Brookite, anatase, rutile, barite, magnetite and enlargement of tourmaline and zircon particles are other minerals which form under unknown sedimentary conditions. It is desirable that these conditions should be learned. Until that is done one does not know the significance of these authigenic substances in sediments.

### ENVIRONMENTAL STUDIES

Any environment is due to the concurrence of a vast variety of factors. Some factors are very obvious, others are difficultly determinable. Some factors are biologic and others are physical and chemical not related to organisms. All factors responsible for any natural environment are determined with great difficulty and, perhaps, in the present state of knowledge, impossible of determination. Moreover, the entrance of a single new factor into a natural environment may completely change its biological assemblages and ultimately its sedimentary consequences.

The lagoons and bays of the Gulf Coast offer problems of primary importance. Sediments of some of these lagoons contain much organic matter, but no one seems to know what is taking place in these sediments after they are deposited. Is the organic matter gradually being generally eliminated, or is it locally eliminated? Are there places where the organic matter is being buried with little alteration? If these differences exist, what are the conditions responsible for them? Are the sediments beneath the bottom different from those at the surface of the bottom? To what are these differences, if present, due? If there is elimination of organic matter, to what agencies is the elimination due? It probably will be found that microorganisms are largely responsible. What are these microorganisms and what are they producing from the destruction of the organic matter? Are these products changing the sediments not directly modified by the microorganisms? Are there any organic substances that are not affected?

It has been suggested that the oils in the Gulf Coast and other sections origi-

nated in sediments not unlike those now undergoing deposition in the lagoons and bays of the present coast. Are there any oily substances now in process of formation? What becomes of the oily matter of plants? What inorganic substances other than clay and quartz are being deposited? Is there deposition of calcium, magnesium, or iron carbonates? Are manganese or iron oxides being deposited? If so, to what is the deposition due?

These and other questions call for answers. These may be expected to be found in marine and lagoonal sediments along the Gulf Coast. The deposits of each lagoon probably constitute an individual problem as has been found for the lake deposits of the upper Mississippi Valley. Study of the deposits should be approached from that point of view.

There are both fresh-water and salt-water lakes on the Gulf Coastal Plain. What are the characters of the sediments deposited in these lakes? Is there anything in the lakes that is comparable to the seasonal overturn of lakes in northern United States? Are the bottom waters provided with oxygen or are they filled with substances that are deleterious to organisms. What is the distribution of microorganisms in the lakes? To what extent are microorganisms active in lakes and to what depths in the bottom sediments do the activities extend? Are the organisms like those of northern lakes? Do they have the same distribution? Are the bottom waters eutrophic, oligotrophic, or dystrophic? What happens to organic substances deposited in these lakes? Do the sediments exhibit changes with depth? Many northern lakes contain oils in the sediments. Do the sediments of southern lakes contain oil? These and many other questions press for answers.

### LITHIFICATION OF SEDIMENTS

Lithification of sediments is largely a little understood field. There are places in the Tertiary sediments of the West Gulf Coast where the sediments are firmly cemented and other places where the same sediments are still loose bodies of sands. Why is this the case? Has anyone attempted to find out? Perhaps an explanation can not be discovered but some facts bearing on the problem should be possible of discovery.

### SUMMARY

It is hoped that the foregoing discussion and the questions raised may serve to show that there are still frontiers to sedimentary mineralogy and petrography, that there are many places that really bristle with problems and that there is a broad expanse that is unexplored. It is hoped that what has been said may serve to stimulate some to undertake the solution of some of these problems. What has been said applies to the West Gulf Coast and neighboring regions. It is thought, however, that there are few places of the earth's surface where problems are not as numerous and where the possibilities of advancing the known into the unknown are not equally favorable.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 64–72, PLATE 1, FIGS. 1–5, TABLES 1–4, AUGUST, 1941

# MEASUREMENT AND GEOLOGICAL SIGNIFICANCE OF SHAPE AND ROUNDNESS OF SEDIMENTARY PARTICLES

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## ABSTRACT

Methods are described for the rapid measurement of shape and roundness of large sedimentary particles. Shape is determined from the long, intermediate, and short diameters of the particles, and roundness is measured by a rapid visual method. The importance of distinguishing between these properties is discussed. Shape and roundness behave differently during abrasion and selective transport, and hence are important in evaluating the effects of these processes during the formation of the deposit.

## INTRODUCTION

Two fundamental properties of sedimentary particles which have been much confused are shape and roundness. Some workers apparently consider the distinction a minor one; others recognize its importance, but do do not make the distinction because of the time required. The present paper describes rapid but rigorous methods for the measurement of shape and roundness which reduce the time required per sample to a matter of minutes instead of hours. The paper also discusses the distinction between these attributes on the basis of the behavior of particles during abrasion and transportation to indicate the fundamental importance of the concepts in evaluating the past history of sedimentary deposits.

## SHAPE AND ROUNDNESS

Wadell (1932) was the first to show that the commonly used terms "shape" and "roundness" were not synonymous, but really included two geometrically distinct concepts. The shape of a particle is its form, entirely independently of whether the edges or corners are sharp or round. Fundamentally the shape is a measure of the ratio of the surface area of a particle to its volume. For a sphere, this ratio is a minimum, and for all other forms it is larger. Hence the ratio of surface area to volume indicates how closely or remotely the particle approaches a sphere in form. For practical purposes this ratio is difficult to measure, and the actual measurement is expressed in terms of the ratio of the volume of the particle to the volume of its circumscribing sphere. The cube root of this ratio is called the *sphericity* of the particle.

The roundness of a particle is a measure of the curvature of the corners and edges expressed as a ratio to the average curvature of the particle as a whole, independent of its form. For practical purposes the "average curvature" is expressed in terms of the inscribed circle drawn on a projection of the particle in a plane.

One may gain a clear picture of the difference between sphericity and roundness by making several simple tests on actual pebbles. A pebble is held in such a manner that the forefinger and thumb form a circle about the long axis of the pebble. If the pebble occupies only a small part of this "circumscribed sphere," the ratio of its volume to the volume of the sphere is small, and it has a low sphericity. If the pebble essentially fills the "sphere," it has a high sphericity. To visualize roundness, a different technique is used. The pebble is held with its long axis between the extended thumb and forefinger in such a manner that one views the largest projection of the pebble. The largest inscribed circle which can be drawn on the projection is now visualized, and with this in mind, the radius of each corner on the projection is com-

pared with the radius of the inscribed circle. If the corner radii are small in comparison, the roundness is low. If the radii of the corners are of the same magnitude as the inscribed circle the roundness is high. It may be noted, incidentally, that a pebble of high sphericity may have either high or low roundness, as may a pebble of low sphericity—the two concepts are geometrically distinct.

### RAPID METHOD FOR SHAPE MEASUREMENT

Wadell's method for determining the sphericity of a pebble requires measurement of the volume of the pebble and of its longest diameter. The diameter of a sphere having the same volume as the pebble is then calculated, and the ratio of this "nominal diameter" to the long diameter is the sphericity of the pebble. In the writer's method only the long, intermediate, and short diameters of the pebble are measured; the sphericity is read directly from a chart by means of two ratios between pairs of the diameters. This "intercept method" reduces the time required to a small fraction of the standard method, and yet the average values of the two methods agree within a few per cent.

The writer's intercept method is based on a triaxial ellipsoid as the reference solid to which the pebble is compared.[a] It is therefore necessary to define the three diameters of the pebble as mutually perpendicular intercepts. This requires some care in choosing the proper diameters to measure. For accurate work a formal routine is followed, which may be even further shortened for approximate field measurements. The formal routine requires at most between one and two hours for 50 pebbles; the field method reduces this to about 30 minutes.

The formal routine is described in detail to establish the principles involved; thereafter the shortened versions may be adjusted to the needs of the individual worker. In measuring the diameters it is convenient to have a sliding rod of the type shown in figure 1. The steps involved are:

1) The pebble is held in position and the longest intercept through it is measured as shown in figure 1.
2) The pebble is then held between the thumb and forefinger by the ends of this longest diameter, and rotated until the largest sec-

[a] The mathematical theory on which the intercept method is based is given in the Appendix at the end of this paper, which also gives comparative figures on the accuracy of the method.

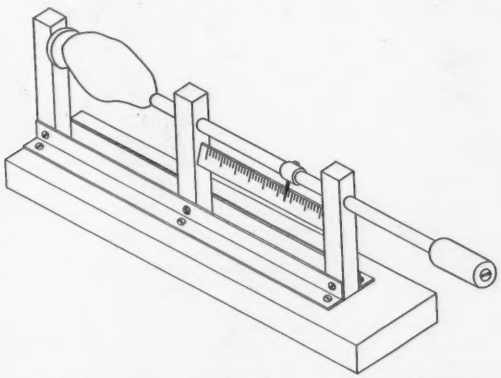


FIG. 1.—Sliding rod caliper for measuring pebble diameters. The rod and uprights are brass, and the device is mounted on a wooden base.

tion is seen by the eye. (This is equivalent to finding the position in which the pebble would cast its largest shadow in a parallel light beam.)

3) The pebble is held with this "maximum projection plane" horizontal, and the widest part is measured in a direction perpendicular to the long axis. (See figure 2, left.)

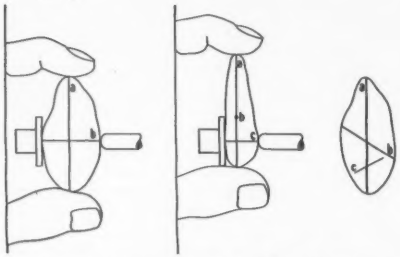


FIG. 2.—Measurement of pebble diameters. *Left*, the b-axis in position; *center*, the c-axis in position. *Right*, the pebble in perspective.

4) With the pebble still held by its long diameter, the maximum projection plane is rotated to a vertical position, which places the short pebble diameter in a horizontal plane.

5) The widest part of the pebble in the horizontal plane is measured, also perpendicular to the long axis. This is the short diameter of the pebble. Figure 2 (center) shows this step, and figure 2 (right) shows the three axes through the pebble. It may be noted that the three diameters do not necessarily intersect at any one point, although they are mutually perpendicular.

The three diameters are designated as *a*, *b*, and *c* for the long, intermediate, and short axes respectively, and are recorded as shown in table 1. Two ratios are then determined with a slide rule, and entered in adjacent columns. The first is the ratio of the intermediate to the long diameter ($b/a$), and the second is the ratio of the short to the intermediate diameter ($c/b$). To determine the sphericity, these ratios are laid off on the axes of the chart (figure 3), and where the values intersect

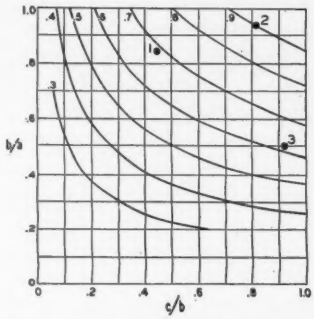



FIG. 3.—Chart for determining sphericity. The curves represent lines of equal sphericity. The numbered circles refer to the examples in table 1.

in the diagram the sphericity may be read off to the nearest two-hundredths. The figure shows the location of the three pebbles in table 1, and the corresponding interpolated sphericities are entered in the last column of the table.

The space required for describing the method is out of proportion to the time actually required, but it insures an added accuracy if the diameters are measured as indicated. The use of a table and the calculation of the ratios may be eliminated by using an "eye-ratio" method which is suitable for rough field measurements. The pebble is held with its long axis lined up with a pencil, and the length of the long axis is indicated by setting

TABLE 1. *Arrangement of data for intercept sphericity*

| Pebble | Long Diameter in mm.(a) | Intermediate Diameter (b) | Short Diameter (c) | $b/a$ | $c/b$ | $\psi$ |
|---|---|---|---|---|---|---|
| 1 | 45 | 38 | 17 | 0.84 | 0.45 | 0.68 |
| 2 | 51 | 48 | 39 | .94 | .81 | .90 |
| 3 | 48 | 24 | 22 | .50 | .92 | .62 |

the thumb nail on the pencil. The pencil is then held parallel to the intermediate diameter, and the ratio estimated by eye to the nearest tenth. This yields the $b/a$ ratio. The thumb nail is then moved to indicate the length of the intermediate diameter, and the pencil held along the short diameter to estimate the $c/b$ ratio. These two ratios are then located on the chart and the sphericity read off.

Regardless of whether the formal routine or the eye-ratio method is used, it should be emphasized that individual pebbles may not agree closely in value with the true sphericity as measured by Wadell's method. However, sets of 25 or more pebbles will afford an average sphericity value very close to Wadell's average value. The average sphericity is found by adding the individual sphericities and dividing by the number of pebbles. The lack of agreement between individual pebbles is due to the fact that whereas single pebbles may not be approximated very closely by a triaxial ellipsoid, a group of pebbles will tend statistically to satisfy that condition.

### RELATION BETWEEN SPHERICITY AND ZINGG SHAPE CLASSES

Some years ago Zingg developed a classification of pebble shapes based on the $b/a$ and $c/b$ ratios. The present method of determining sphericity permits a direct reconciliation of Zingg's and Wadell's shape concepts. Zingg set up four classes as shown in figure 4, and defined the classes by the boundaries indicated in table 2. The writer merely combined figures 3 and 4 to obtain figure 5, which affords a standard form for the intercept sphericity. Inasmuch as the intercept sphericity is based on any values of $b/a$ and $c/b$, these ratios may be plotted as points on figure 5, whereupon not only may the sphericity be read, but the pebbles are automatically classified according to Zingg. If the reader will draw the lines of figure 4 on figure 3, he will see that pebble 1 of table 1 is a disk, pebble 2 is spherical, and pebble 3 is cylindrical or rod-shaped.

TABLE 2. *Zingg's classification of particle shape*

| Class | $b/a$ | $c/b$ | Shape |
|---|---|---|---|
| I | >2/3 | <2/3 | Disks |
| II | >2/3 | >2/3 | Spherical |
| III | <2/3 | <2/3 | Blades |
| IV | <2/3 | >2/3 | Rod-like |

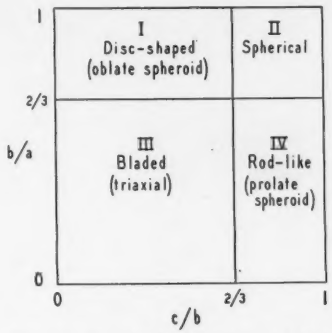



FIG. 4.—Zingg's classification of pebble shapes. (See table 2.)

In practice, the writer uses a separate sheet for each sample of pebbles, with the values indicated by dots, whereupon they may be visualized as a population. The average values of the $b/a$ and $c/b$ ratios may be plotted as a triangle, to indicate the average sphericity of the set. In any study of a set of samples the distribution of the points from sheet to sheet affords data for correlations by sphericity, or may be used to study changes in shape due to selective transportation, etc. Comparisons from sample to sample are most convenient when similar size-ranges are used for both. The writer uses the size range from 16 to 32 mm. for rapid comparisons because of the ease of handling that size.

The present method of shape determination does not lend itself to small particles in which the three axes cannot be separately measured. Sand grains at rest on a microscope slide usually have

their short axes nearly vertical, so that the outline seen gives the *a* and *b* axes only.

### RAPID METHOD FOR ROUNDNESS ANALYSIS

Wadell's method for measuring the roundness of a pebble requires drawing an image of the pebble at a standard magnification, and determining the radii of the inscribed circle and of the edges and corners of the image. From these data a ratio is calculated which indicates the relative size of the average radius of curvature to the radius of the inscribed circle. This value is the *roundness* of the pebble.

In the writer's method the pebble is compared with standard images of known roundness, and a roundness value assigned to it. The visual roundness method is not a qualitative estimate of roundness such as is commonly used to describe pebbles. The images used for comparison were redrawn from pebbles which were measured by Wadell's method, and statistical studies have shown that the average values agree well

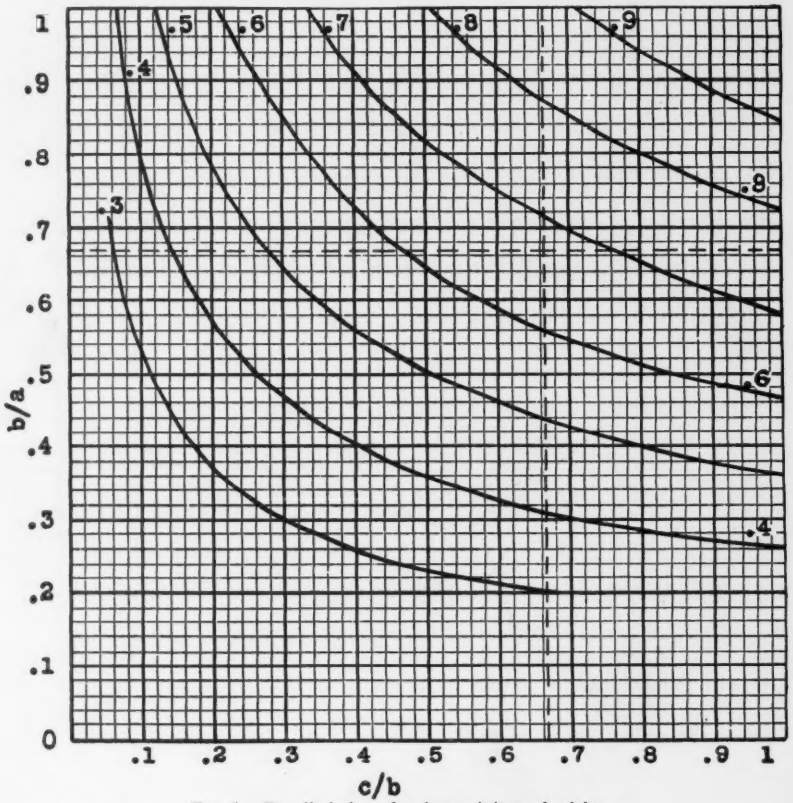



FIG. 5.—Detailed chart for determining sphericity.

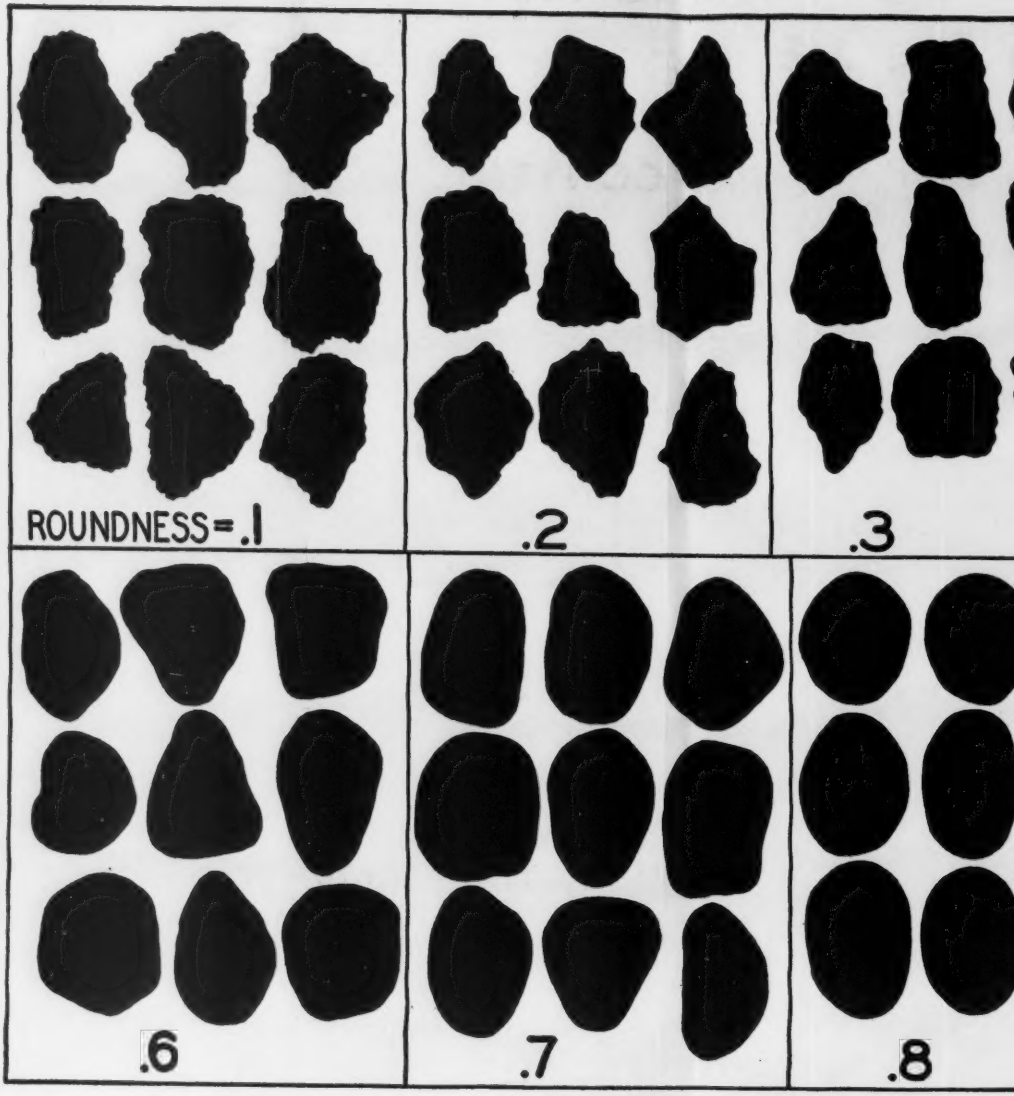
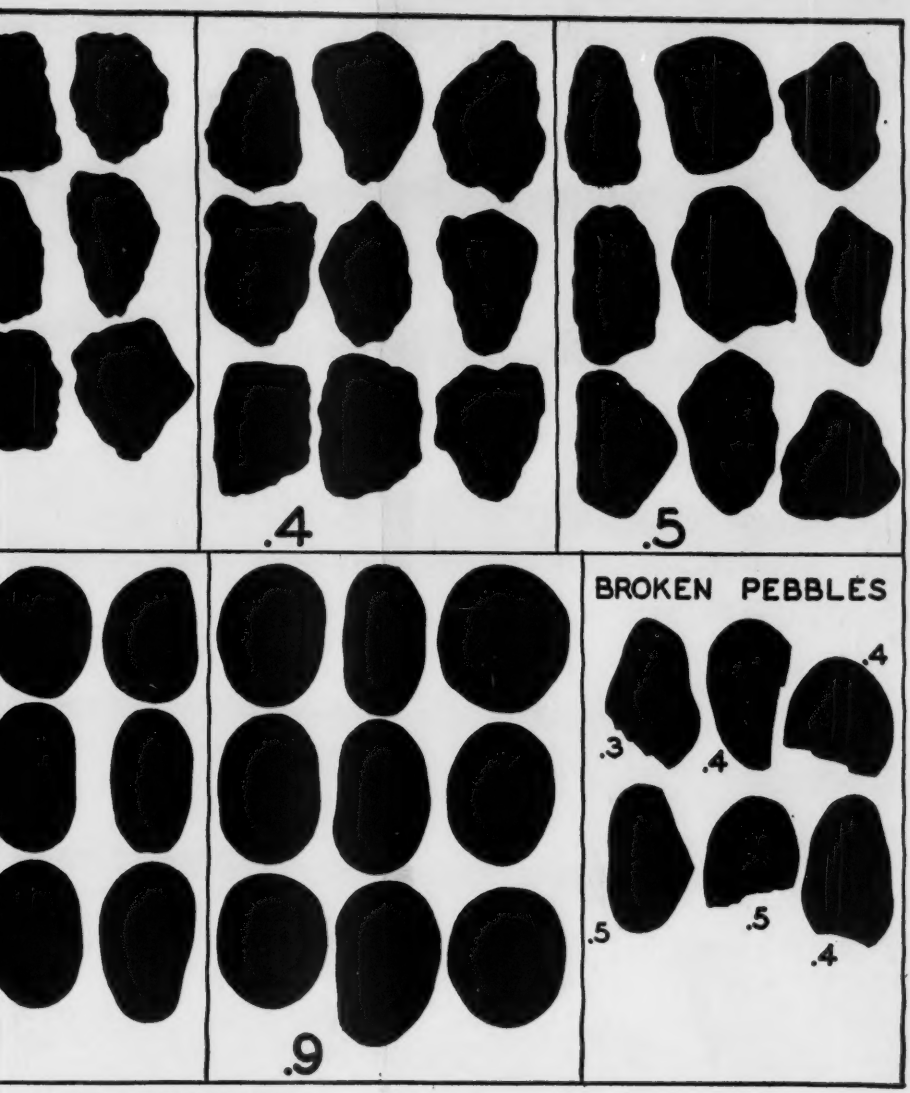



PLATE 1.—Roundness chart for 16–3

Plate 1




VISUAL ROUNDNESS

for 16–32 mm. pebbles.

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TILDEN FOUNDATIONS.

with Wadell's values. (See Appendix for details.)

Plate 1 has ten sets of standard images, with long diameters of about 25 mm., for use directly with pebbles in the 16–32 mm. size range. The sets vary in roundness from 0.1 to 0.9. Several broken pebbles are also shown, to indicate the effects of such breakage on roundness. By enlarging or reducing the images photographically, similar sets may be made for any size range. In using the figures, the pebble is held with its long axis between thumb and forefinger in such a manner that one sees the largest projection of the pebble. In this position, the pebble is held against a contrasting background and viewed in silhouette. It is compared with the images, and a value assigned to it. For example, if the pebble is matched by one in the third rectangle from the left, upper row of plate 1, the value 0.3 is assigned to it. A set of pebbles (preferably about 50; but at least 25) is so measured, and the average roundness calculated. The time required is perhaps 30 minutes for 50 pebbles.

In determining the average roundness, a rapid tally method is convenient, as shown in table 3. The first column lists the roundness values; the second column shows the number of pebbles in the sample having these values. The values in the third column are found by multiplying column 1 by column 2. The sum

TABLE 3. *Tally sheet for computing mean roundness*

| Roundness, $P$ | Number of particles, $f$ | $P \times f$ |
|---|---|---|
| 0.2 | 3 | 0.6 |
| 0.3 | 7 | 2.1 |
| 0.4 | 19 | 7.6 |
| 0.5 | 12 | 6.0 |
| 0.6 | 9 | 5.4 |
| | 50 | 21.7 |

of the third column is divided by the number of pebbles to obtain the arithmetic mean roundness. In the example this value is $21.7/50 = 0.43$.

Certain precautions should be followed in determining roundness visually. The pebble should be viewed only in the position specified, because this agrees with the routine originally established by Wadell, and corresponds statistically to the position of rest of pebbles and sand grains when viewed from above. Wadell's roundness is thus expressed in terms of the maximum projection plane of the pebble. There can be no objection to any other orientation if one wishes to use it, except that the values in that case cannot be directly compared with Wadell's values. Similarly, by using arbitrary numbers for each class, a roundness value may be obtained, but again the numbers cannot be directly compared.[2] It is also important to notice all the smaller corners and edges in the silhouetted pebble, because it is these small curvatures which largely control the roundness value. A comparison of the several images in plate 1 will indicate the importance of this point. Rounded pebbles which have been broken require special precautions because the sharp corners on the broken edges reduce the average roundness very markedly. An approximate rule to follow in such cases is to assign a roundness number to the unbroken part of the pebble, and then to halve this number. If the rounded part is matched by a pebble of roundness 0.8, the number to assign to the pebble is 0.4. For odd values, as 0.7, use the smaller half, 0.3. The several examples in the lower right rectangle of plate 1 show actual values.

In any study of roundness, it is advisable to divide the pebbles into size classes and to determine the average roundness for each size class separately. There generally is a marked difference in the roundness of different sized particles in any given sample, so that compari-

[2] Russell and Taylor, for example, used a visual method in which standard sets of grains were numbered arbitrarily, although the original grains had been measured by Wadell's method. The arbitrary numbers varied from 1 up, which departs from the geometrical picture of Wadell's roundness, inasmuch as the latter measures the approach of the curvature of the corners to the curvature of the particle as a whole, and hence varies from 0 to 1. (See R. Dana Russell and R. E. Taylor, "Roundness and shape of Mississippi River Sands," *Jour. Geol.*, vol. 45 (1937), pp. 225–267.

sons from sample to sample are more convenient in terms of a restricted range of sizes.

The roundness figures are suitable for particles of any size, and by using enlargements or drawings of loose grains under the microscope, their roundness may be found as with pebbles. For the binocular microscope a set of photographs from plate 1, reduced to the same scale as the apparent grain size seen by the eye, may be used for rapid estimates.

## IMPORTANCE OF SHAPE AND ROUNDNESS IN SEDIMENTARY STUDIES

Geologists are interested in sediments in part for the light they shed on the source of the material, the distance of transport, and the environmental conditions under which the deposit was formed. The basic assumption in these studies is that each sediment is a response to a definite set of environmental conditions, and that the properties of the sediment reflect these conditions to a greater or lesser degree. Reconstruction of the environment, therefore, depends upon an interpretation of the properties of the sediment, supplemented by studies of the fossil content of the rocks and other features.

This point of view is held in common by most workers, but its full implications are sometimes overlooked. Among points often not emphasized is the important one that it may not be possible, *a priori*, to predict which specific properties of the sediment will be most important in interpreting any particular part of its history. Some workers concern themselves with one or two quantitative features of the sediments, such as heavy mineral content or size of particles, and base their interpretations on them. These two are not by any means the only quantitative characteristics of sediments which reflect their history, and it is not even certain that they are the most significant.

The fundamental properties of sedimentary particles are size, shape, roundness, mineralogical composition, surface texture, and orientation. (The latter refers to the orientation in space of the principle axes of the particle while it remains in its parent deposit.) These six attributes control such mass properties as color, average density, porosity, permeability, "fabric," and so on. The complete study of sediments should, therefore, include all the fundamental properties, as well as the mass properties and other characteristics of the rock.

The present paper is concerned mainly with shape and roundness, for which relatively few generalizations have been established, inasmuch as few sedimentary studies have included rigorous investigations of these properties. It seems safe to say, however, that roundness is strongly modified by the abrasion and wear to which particles are subjected, whereas shape may play its most important role in the selective transportation of the particles.

The importance of shape in selective transportation is indicated by the fact that the three properties of particles which control their settling velocities are the size, shape, and density (mineralogical composition). The settling velocities, in turn, are of fundamental importance in the hydrodynamic behavior of the particles. Changes in the dynamical conditions of transport, accordingly, are reflected by changes in the size, shape, and density of the deposits. Further, the ratio of surface area to volume (which is fundamentally what sphericity represents) is important in controlling the response of particles to lifting forces, so that particles of low sphericity may behave differently from particles of high sphericity during transportation. Thus the shape, in conjunction with size and density, should shed light not only on the transportational history of the deposit, but also on the immediate conditions at the site of deposition.

Settling velocity is essentially independent of the roundness of the particles. Hence changes in the conditions of transportation or deposition may not reflect themselves in rounding, except as such changes may affect the rate of wear of

the particles. Roundness is extremely sensitive to abrasion, and angular particles change rapidly in their roundness during movement. After the initial stages of rounding the process is much slower. During ordinary abrasion, shape is relatively stable, and the original form is often reflected in the pebble even after considerable wear. Under impact breakage shape may change rapidly. Just what the relative effects are must be determined experimentally, because they depend upon the response of particles to forces of different magnitudes.

Analysis of the dynamics of particle wear and transportation is only in its initial stages, and relatively few rigorous principles have been established, which can be applied directly to sedimentary studies. Some progress has been made, however, and considerably more may be anticipated as studies of shape and roundness become more common. The reader is referred to the excellent articles by Hjulström (1939) and Russell (1939) in *Recent Marine Sediments* for summaries of present knowledge in these subjects. A review of abrasion studies, and an analytical approach to the problem are given in a recent paper by the writer (1941).

## APPENDIX

### Theory of Intercept Sphericity

Wadell's definition of sphericity ($\Psi$) may be stated as follows:

$$\Psi = \sqrt[3]{\frac{\text{Volume of the particle}}{\text{Volume of the circumscribed sphere}}} \qquad (1)$$

Waddell expressed the volume of the particle in terms of a sphere having the same volume; the diameter of the corresponding sphere is the "nominal diameter" ($d$) of the particle. On this basis the volume of the particle is $(\pi/6)d^3$. The volume of the circumscribed sphere is in general based on the longest diameter ($a$) of the particle, so that the volume of this sphere is $(\pi/6)a^3$. By substituting these values in equation (1), Wadell's sphericity reduces to the ratio of the nominal diameter of the particle to its longest diameter:

$$\Psi = \sqrt[3]{\frac{(\pi/6)d^3}{(\pi/6)a^3}} = \sqrt[3]{\frac{d^3}{a^3}} = \frac{d}{a}. \qquad (2)$$

For the intercept sphericity, the writer uses the same basic definition (equation 1), but expresses the volume of the particle in terms of a triaxial ellipsoid having the three diameters $a$, $b$, and $c$, where $a > b > c$. The volume of such an ellipsoid is $(\pi/6)abc$. Inasmuch as the volume of the circumscribed sphere is still $(\pi/6)a^3$, these two volumes may be substituted in equation (1), yielding:

$$\Psi = \sqrt[3]{\frac{(\pi/6)abc}{(\pi/6)a^3}} = \sqrt[3]{\frac{bc}{a^2}}. \qquad (3)$$

This equation is simplified by cubing both sides, to eliminate the radical sign:

$$\frac{bc}{a^2} = \Psi^3. \qquad (4)$$

In order to express the sphericity in terms of the ratios $b/a$ and $c/b$, equation (4) is manipulated to yield the one ratio on the left hand side and the other on the right. This is done by first dividing through by $c$, and then multiplying by $b$, in such manner that the $b$ is placed in the numerator on the left, and in the denominator of a compound fraction on the right:

$$\left(\frac{b}{a}\right)^2 = \frac{\Psi^3}{(c/b)}. \qquad (5)$$

Equation (5) is the form on which the hyperbolic curves of figure 5 are drawn. It is an equation of the type $y^2 = k/x$, where $y = b/a$, $k = \Psi^3$, and $x = c/b$. The sphericity was set equal to 0.3, 0.4, $\cdots$, 0.9 successively, and the corresponding curves of figure 5 were calculated. Values of sphericity lower than 0.3 were not included, because of their rarity in nature. If desired, the additional curves may be drawn from values based on equation (5).

It may be seen from this development that the writer's method is based on Wadell's definition of sphericity, so that if actual triaxial ellipsoids were used, the true sphericity could be found from the chart or from equations (4) or (5). Pebbles are not triaxial ellipsoids, but statistically they may be approximated by such a form, so that in practice an excellent agreement is found between the

TABLE 4. *Comparison of standard and rapid methods for measuring shape and roundness*

| Sample | Size range (mm.) | Sphericity | | | Roundness | | |
|---|---|---|---|---|---|---|---|
| | | Wadell | Intercept | Relative Error, % | Wadell | Visual | Relative Error, % |
| Outwash | 8–64 | 0.74 | 0.75 | 1.4 | 0.61 | 0.60 | 1.6 |
| Outwash | 8–16 | .76 | .75 | 1.3 | .52 | .52 | 0.0 |
| Outwash | 16–32 | .75 | .76 | 1.3 | .58 | .58 | 0.0 |
| Outwash | 32–64 | .76 | .78 | 2.6 | .61 | .61 | 0.0 |
| Till | 32–64 | .71 | .69 | 2.8 | .50 | .50 | 0.0 |
| Till | 8–16 | .72 | .72 | 0.0 | .48 | .49 | 2.1 |
| Till | 16–32 | .72 | .72 | 0.0 | .52 | .50 | 3.8 |
| Till | 16–32 | .73 | .77 | 5.5 | .48 | .54 | 12.5 |
| Till | 16–32 | .76 | .77 | 1.3 | .51 | .59 | 15.7 |

average Wadell sphericity and the average intercept sphericity of the same set of pebbles.

### Accuracy of Rapid Methods

The writer conducted a number of tests on the intercept sphericity and the visual roundness to determine the accuracy of the methods. It was found that for samples of 25 pebbles the average values obtained by the two methods agreed consistently within 5 per cent. During these studies an opportunity arose for a comprehensive test, based on a number of samples. Through the courtesy of Dr. F. J. Pettijohn of the Department of Geology, the students in a graduate course on sediments measured sets of 100 pebbles for sphericity, and sets of 50 pebbles for roundness, using both standard and rapid methods. The samples were all different, and included pebbles from glacial outwash and glacial till, ranging in size from 8 to 64 mm. diameter. Table 4 summarizes the data. The average relative error of the sphericity measurements (based on 100 pebbles) was 1.8 per cent, and the single large error was 5.5 per cent. In the first seven roundness samples the average error was only 1.1 per cent, but the last two samples had errors of 12.5 and 15.7 per cent. These were entirely out of line with the other samples (all were based on 50 pebbles), and a re-examination showed that the large errors were due to the incorrect evaluation of broken pebbles. It was from this study that the approximate rule for evaluating broken pebbles was developed, in which the roundness of the unbroken half is divided by 2.

The students who conducted these tests had had no previous experience with roundness or sphericity measurements. The results of the roundness study emphasized the need for critical examination of the sharper corners and broken edges of the pebbles. With these precautions taken, the average error lies within about 2 per cent for sets of 50 pebbles.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 73–79, FIGS. 1–4, AUGUST, 1941

# A NEW DEVICE FOR SAMPLING LAKE SEDIMENTS

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## INTRODUCTION

The problems involved in securing complete cores of sediment or samples from any depth of water or depth of sediment in lakes presents many difficulties when the deposits are thick, composed mostly of water, or contain much sand. The sampling device described in this paper overcomes some of the difficulties and makes it possible relatively easily to secure uncontaminated samples from all depths. The fact that nearly the whole apparatus is made of standard materials makes it easily assembled at small expense.

## ACKNOWLEDGMENTS

The author is so much indebted to students who have been employed as helpers from time to time as well as to several of his colleagues for suggestions that have been incorporated into the apparatus that he can hardly claim any credit for its merits except a persistence in trying out various ideas and retaining those that worked. However, special mention needs to be made of the contributions of Donald Wohlschlag and Robert Wilson who have worked with the author during the past three summers and of the Division of Fish and Game of the Indiana Department of Conservation which has financed the field work.

## DESCRIPTION OF THE SAMPLING DEVICE

The sampling device consists of two principal parts, namely, the sampler proper (lower part of A, B, and C, fig. 1) and a valve enclosed in a housing (upper part of A, and D, fig. 1).

Three different samplers are used for as many different situations. One (fig. 1B) is used without casing in sediment that coheres well and adheres to the wall of the sampler sufficiently to be easily brought to the surface. This sampler consists of a 13-inch piece of extra-heavy 1¼-inch pipe which has been beveled at the bottom and has been tapped out with a 1-inch standard tap at the top. A 1½-inch standard bushing containing a special distributor (fig. 1D) has been screwed into the top. This bushing adapts the sampler to screw into the ½-inch perforated nipple of the upper part of the sampling device. The distributor is a piece of steel with five ¼-inch holes bored from the center of the top surface to the outer edge of the bottom surface. This is threaded on the outside so as to screw into the bottom of the 1½-inch bushing which has special threads cut into it for the purpose. The distributor directs water against the walls of the sampler, thus assuring its thorough cleansing.

Another sampler (fig. 1C) is utilized when a casing is used in the drilling operations. The casing is necessary when more than 20 feet of sediment are penetrated and the sediment is firm enough to stick in the sampler. It consists of a ¾-inch piece of standard pipe 13 inches long tapered at the bottom and tapped out at the top with a standard ½-inch tap. This adapts the sampler to screw directly onto the ½-inch perforated nipple.

The third type of sampler (bottom part of A, fig. 1) is designed to be used without a casing and in very soft sediment that frequently fails to stick sufficiently to the side wall of a sampler to allow it to be brought to the surface. This sampler is exactly the same as the first one described (1¼-inch extra-heavy pipe, etc.) except that it has an iris diaphragm fastened at the bottom (fig. 1A and 1E) and a diaphragm closing device surrounding it. The iris diaphragm

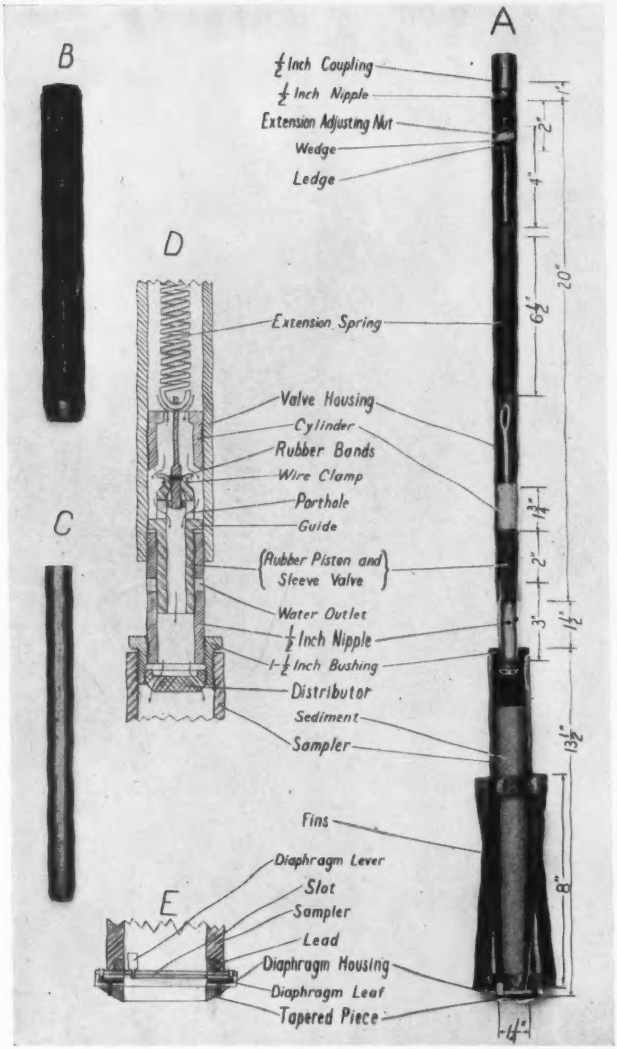


FIG. 1.—*A*. The sampling device cut out to show the details of construction. The upper part is referred to in the text as the valve enclosed in a housing; the bottom part is the sampler with an iris diaphragm and diaphragm closer (fins) used in the very soft sediment without a casing. *B*. The same sized sampler as shown in *A* except that there is no diaphragm or diaphragm closer. This sampler is used without casing in sediment that is solid enough to stick in the sampler without aid. *C*. This is the ¾-inch sampler used when working inside a 1¼-inch casing. *D*. Drawing showing the sleeve valve and piston when water is being pumped through it.

is the lever-closing type that screws into an adapter on the sub-stage of a student compound microscope.

The bottom of the 1¼-inch sampler is cut out and threaded on the inside to receive the diaphragm (fig. 1E) which is screwed into it. The offset on the inside of the sampler resulting from this cutting is filled in with lead to make it flush with the inside of the sampler. Since the opening of this diaphragm is slightly less than 1¼ inches it has to be enlarged to that dimension so that the edges of the leaves and the diaphragm housing are flush with the sampler. This can be done without impairing the diaphragm's efficiency too much by grinding with a small high speed carborundum wheel. The diaphragm lever which ordinarily projects horizontally is turned up vertically so that it is parallel with the sampler and in a position to be pushed closed by the diaphragm when it rotates. A tapered ring of steel with a 1¼-inch opening is fastened to the bottom of the diaphragm with screws so that a sharp edge sloping away from the sampler opening is presented to the sediment, thereby avoiding eddy currents when the sampler is being driven into a deposit.

The diaphragm closing device (fig. 1, lower part of A) consists of four fins made of heavy gage sheet iron soldered to two metal rings that fit loosely around the sampler. The lower ring has an offset that permits a small pin set into the sampler to act as a stop so that no strain is put on the diaphragm lever when the fins push against it while holding it opened or closed. The fins are set at a slight pitch so that the diaphragm closer tends to rotate clockwise on the sampler during its descent, thus keeping the diaphragm open. When the desired level for sampling has been reached and the sampler driven into the sediment the sampler is rotated clockwise to close the diaphragm. The diaphragm closer remains stationary during this process due to the fact that its fins are embedded in the sediment. The pitch of the fins tend to keep the diaphragm closed as the sampler is raised to the surface. Larger or smaller fins can be used according to the consistency of the sediment.

It is obvious that the leaves of the iris diaphragm described above would be damaged if used in anything except soft, fine-grained sediment such as occurs in the upper levels of a deposit. It is advisable to carry extra sets of leaves in the field in order to make repairs if some become damaged. If the rivets of the diaphragm leaves are securely fastened they stand up under a surprising amount of strain.

Glass tubes, or such heavy parafined paper tubes as Rawson (1930) used in his "Heavy Sampler Set," may be inserted into any of the above samplers before use and removed with the sample afterwards. If such tubes are corked and made air-tight, the samples keep unchanged indefinitely.

The second principal part of the sampling device, namely, the valve enclosed in the housing, is shown in perspective in the normal resting position in the upper part of A, figure 1. A drawing showing more details of the valve as it appears when water is being forced through it is shown at D.

The purposes of this mechanism are threefold. First, to leave open several holes in the ½-inch nipple (above the sampler), as the sampler is being driven into the sediment, so that the water in the sampler can escape as the sediment comes in. Second, it closes the same openings (fig. 1D) when water is being pumped through the sampler as it is lowered through the sediment to the desired level to secure a sample, thus making certain that all the water passes out the distal end of the sampler. This gives the maximum washing effect on the sediment both within and in front of the sampler. Third, when the sampler, especially the B or C types, is being raised to the surface the hydrostatic pressure which develops, as the long pipes (20-foot sections) are raised above the water level, is prevented from forcing the sample out by the rubber piston which is held

in the cylinder by the extension spring.

The spring part of the apparatus is a standard ⅝-inch extension spring of considerable strength. It has a 4-inch slightly modified ¼-inch eyebolt fastened to it at each end. The upper one is threaded throughout its length and is suspended by a ledge and wedge. The ledge is made of a short piece of ½-inch pipe thread screwed into the ¾-inch housing which has been tapped out with a standard ½-inch tap. The wedge is made of a small piece of metal bored so that the eyebolt runs through it. It rests on the ledge on its sharp edge. This piece is inserted between the nut of the eyebolt and the ledge in order that the flow of water will not be obstructed. The tension on the spring can be adjusted by the extension adjusting nut so that the rubber piston and valve barely supports the column of water referred to above when the tubing (½-inch pipe) is raised above the water surface to be disconnected.

The lower eyebolt (attached to the lower end of the spring) is fastened to the rubber piston and valve and passes through the top opening of the cylinder. Its diameter has been considerably reduced by grinding so that it obstructs the opening in the top of the cylinder as little as possible.

The cylinder is made of a piece of metal 1¾ inches long bored out 1½ inches with a ⅝-inch drill and the rest of the way with a ⅜-inch drill. This leaves a ledge at the upper end of the cylinder that acts as a valve seat for the rubber piston. The cylinder is beveled at the bottom so that the rubber piston does not stick on the sharp ledge that otherwise would be present. The length of the cylinder is determined by the distance the rubber piston and sleeve valve needs to travel down the ½-inch nipple (above the sampler) in order to cover the water outlets. The cylinder is fastened solidly to the housing by a metal pin running through a small hole bored through both of them.

The rubber piston and sleeve valve (fig. 1D) are made of a piece of fairly stiff rubber tubing with a ⅜-inch bore and ¼-inch side wall (⅞ inches overall) by grinding off the outside on a high-speed, fine-grained grinding wheel to a size that comfortably fits into the cylinder at the upper end and into the ½-inch nipple at the lower end. A guide is made by leaving most of a ¼-inch portion of the original wall of the tubing to fit snugly into the ¾-inch housing. This guide also prevents the tubing from collapsing under pressure when the pump is running and at the same time prevents water from escaping between the sleeve and the ½-inch nipple. Two portholes are cut into the tubing just above the guide for the entry of water. The rubber piston and sleeve valve is fastened to the bottom end of the lower eyebolt by a wire clamp just above the eyebolt nut. This causes the upper end of the tubing to flare out slightly. By putting rubber bands (String or wire will do as well) in the circular groove between the rubber and eyebolt shaft at this point the amount of flare can be increased or reduced by tightening or loosening the eyebolt nut, thus fitting it with exactly the right snugness into the cylinder to make it act as a piston. Rubber is used for the piston and sleeve valve in order to avoid difficulty when working in sand where a metal valve may frequently "freeze."

## GENERAL PROCEDURE

Samples of sediment are secured by making borings through the floor of an anchored float which is buoyed by oil drums and upon which a derrick is mounted (fig. 2). The derrick is not only convenient for hoisting apparatus but also for handling the 20-foot lengths of pipe used in the sampling operations in deep water and to support a pulley over which a hose passes that connects the sampling apparatus to a force pump (fig. 3). A windlass is built into one end of the derrick to aid in raising heavy anchors. The float can be towed from place to place with an ordinary rowboat powered with an outboard motor. The whole apparatus can be dismantled,

folded up, loaded upon a trailer, transported from one lake to another behind a touring car or truck and reassembled ready for use in one day's time (fig. 4). Obviously, any kind of adequate float could be used.

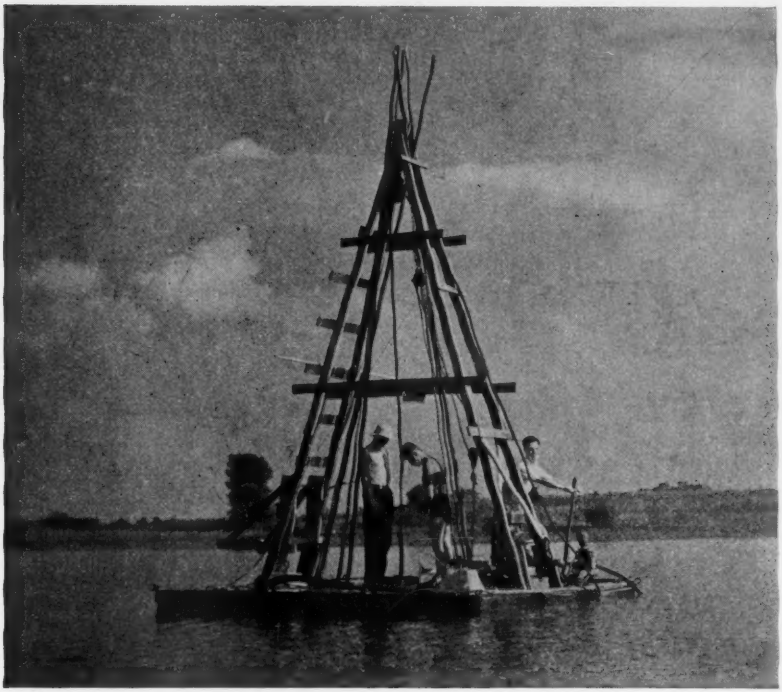

FIG. 2.—The float from which borings are made. A windlass projects from between the two uprights of the derrick at the left. A cement anchor (not in use) can be seen in the foreground. The hand operated force pump shows at the extreme right. Between the two boys in the center of the float the 1¼-inch casing can be seen projecting about 2 feet above the floor and extending from it the tubing (½-inch pipe) which is connected to a hose that runs over a pully (suspended from the top of the derrick) and down the outside of the derrick (right) to the pump.

In making a boring, the sampling device is attached to lengths of ½-inch pipe adequate to reach from the surface of the sediment to a distance considerably above the floor of the float. The top end of this pipe is then attached to a hand force pump by a hose that runs through a hay-loft type of pulley suspended from the apex of the derrick. Next, water is forced out of the sampler as it is gradually lowered to the level in the sediment at which a sample is desired, additional ½-inch pipe being added as needed. During this operation the water discharging from the lower end of the sampler washes a pathway from the sampler and at the same time keeps it clean. When the desired level is reached for sampling the pumping is stopped, the hose is disconnected and the sampler is driven with a

sledge hammer into the undisturbed sediment, a piece of wood being placed over the end of the pipe to avoid damage.

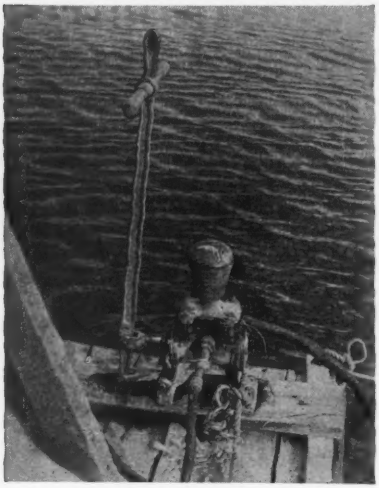

FIG. 3.—The force pump used to wash out the casing and sampler. This type of pump stalls whenever the outlet gets stopped up thus making it certain that when it works the sampler is being washed clean.

Pounding is resorted to even if the sediment is soft in order to secure the advantage of the inertia of the sediment as it is thrust into the sampler. The sampler is never driven into the sediment deeper than it is anticipated that the sediment will rise therein since it is impossible otherwise, to know from what level a sample comes. The length of sample that can be secured varies considerably with different kinds of sediment but seldom exceeds a foot. The sampler is then brought to the surface and the sediment extracted by attaching the sampler to the hose and pump and carefully forcing water into it, the water pressure being easily controlled by bending and releasing the hose.

In attempting to secure a complete core by the above technique some loss is incurred between samples. This difficulty can be overcome when the need justifies the expenditure of time by drilling two holes simultaneously about two feet apart and staggering the samples so that the middle of one comes at the break (where loss occurred) in the other.

Casing is necessary if depths of sediment are to be penetrated. A pipe larger than the sampler is lowered to the level in the sediment at which a sample is desired. Sediment will rise some distance in the casing during this operation. The sampler and attached tubing ($\frac{1}{2}$-inch pipe) are then lowered inside the casing to the level of the sediment in the casing, the hose attached and water pumped through it as before. This washes the casing clean as the sampler is lowered to its bottom and the washings return to the surface between the two pipes. The hose is then detached and the sampler driven into the undisturbed sediment below the casing, brought to the surface and the sample discharged as before.

The advantages of working inside a casing are several. First, one is assured

FIG. 4.—The float folded and maneuvered onto a trailer ready to be pulled out of the lake. When pulled on shore the trailer is fastened to a touring car or truck.

when taking several samples from the same place or securing a complete core that he is returning to the same hole for each succeeding sample. Second, between the recovery of each succeeding sample only the debris that comes into the casing as it is lowered to a new level needs to be washed out, whereas, when working without a casing it is necessary to continue the washing process all the way from the surface of the sediment until the desired level for sampling is reached, a difficult task if more than 15 or 20 feet of sediment are penetrated. Third, in case a stratum of sand is penetrated the casing walls it out so that it does not bother deeper sampling by caving in. Fourth, a casing solidly embedded in the sediment and held taut by its attachment helps to anchor the float and prevents the tubing from buckling when pushing or driving the attached sampler into the sediment.

A disadvantage in working within a casing is that a smaller sampler must be used than where no casing is involved since a 1¼-inch standard pipe is about as large a casing as can be handled on a small float. This size of casing will permit the use of a ¾-inch sampler as a maximum.

Samples representing complete cores of sediment have been secured by the procedure described in water 120 feet deep with 60 feet of underlying sediment. No doubt the same technique could be used in considerably greater depths of water and sediment.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 80–84, FIGS. 1–3, TABLE 1, AUGUST, 1941

# SEDIMENTS OF PECOS RIVER, NEW MEXICO

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## ABSTRACT

The source of the Pecos River is in the Pre-Cambrian rocks of the Sangre de Cristo Mountains, New Mexico. From the mountains the course of the river is to the south-southeast, where it flows over successively younger exposures of Pennsylvanian, Permian, and Triassic formations. The sediments in the tributaries of Rio Hondo and Rio Felix are of both igneous and sedimentary origin. The maximum size of the sands is in the $\frac{1}{2}$ to $\frac{1}{4}$ mm. range and sands in this range increase from 34 per cent of the total at Dilia to 64 per cent at Carlsbad. The heavy minerals transported by the river are magnetite, ilmenite, garnet, epidote, hematite, rutile, purple and transparent zircon, and green, rose, black, blue, and brown tourmaline.

The drainage system of the Pecos River lies almost entirely within the Pecos Valley section of the Great Plains Province of the Interior Plains Division. The river has its source on the south side of Truchas Peak in the Sangre de Cristo Mountains, which are the southern extension of the Rocky Mountains. From Truchas Peak, the stream flows southwest as far as the town of Pecos, New Mexico, where it swings southeast. This south by southeast course is maintained into the Big Bend region of Texas.

At its headwaters the Pecos River is a small, swift mountain stream flowing in a youthful valley. It has cut deeply into, and in places through, the rocks of Magdalena group (Pennsylvanian). In this region the Magdalena consists of conglomerates, sandstones, limestones, gray to black shale, some red beds and coal seams. The Magdalena group overlies the Pre-Cambrian complex of the Sangre de Cristo Mountains. This complex consists of granites, gneisses, schists, and other crystalline rocks. On the divide, paralleling the Pecos, there are biotite schists and fine grained granites.

Southward from the Magdalena, the Pecos flows over successively younger outcrops of Permian and Triassic. The Permian is represented by the Abo formation, a dark reddish brown sandstone, and the Chupadera, consisting of limestone, sandstone, and gypsum. The Dockum group of the Triassic consists of "Red Beds," light grey sandstones, and gypsum.

Two tributaries, Rio Bonita and Rio Ruidosa, which rise in the foothills of Sierra Blanco Mountains, constitute the headwaters of the Rio Hondo. The sedimentary rocks of this region are limestones of the Chupadera formation sandstones and siltstones; red beds of the Dockum formation; and Cretaceous sandstones and shales. The igneous rocks of the Sierro Blanco Mountains are principally monazite porphyry and fine grained granite.

The Rio Felix rises west of the Pecos Valley and flows into it about midway between Roswell and Carlsbad. Throughout its course it flows over limestones, sandstones, red sandstones and siltstones, and gypsum of the Chupadera formation.

### METHOD OF PROCEDURE

Samples were collected from the Pecos River near the towns of Dilia, Santa Rosa, Fort Sumner, Roswell, Artesia, and Carlsbad. The collected samples represent a cross section of the stream deposits. In the laboratory, 25 grams of each sample were sieved and the heavy minerals of specific gravity of 2.9 or more were removed with bromoform. With the aid of a microscope, the heavy minerals were identified and counted. Quartz

grains were classified as to the amount of abrasion into rounded, sub-rounded, sub-angular, and angular.

### CHARACTERISTICS OF THE SANDS

The source rock for the sands in the Pecos drainage system include Pennsylvanian, Permian, and Triassic sediments, post Carboniferous porphyries, and Pre-Cambrian granites, gneisses, and schists. These rocks produce a variety of minerals among which are quartz, magnetite, ilmenite, garnet, epidote, several varieties of tourmaline, hematite, rutile, and two types of zircon. Minerals of minor importance are feldspar, dolomite, gypsum, and mica.

The observed sediments in the upper Pecos River of the Sangre de Cristo region were cobbles, pebbles, granules, and boulders. The approximate abundance is in the order named.

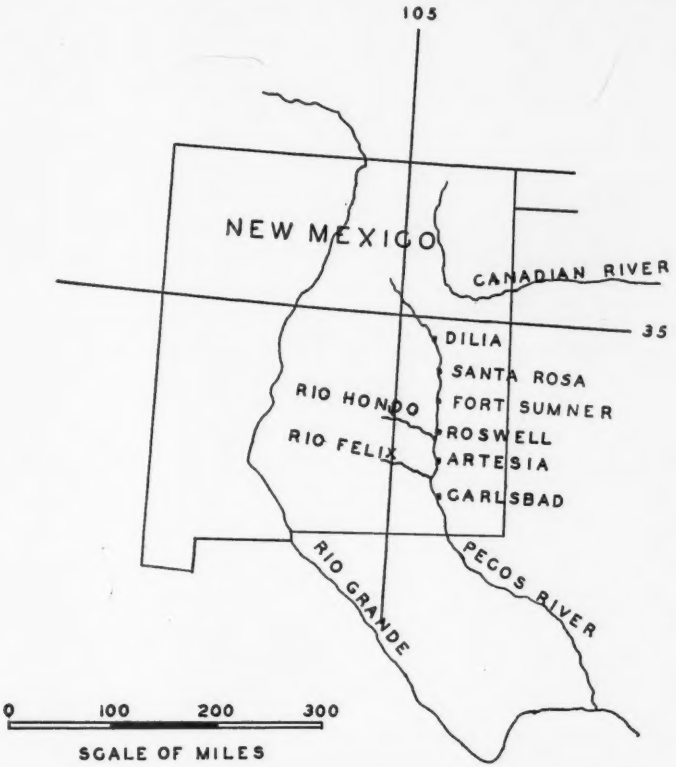


FIG. 1.—Map of New Mexico showing position of Pecos River.

At Dilia, about 50 miles from the source of the river, the deposits are chiefly sand. Here the samples were collected from materials transported in the stream channel and from the deposits which form a low terrace on the concave

side of the valley. Sediments of the terrace are better sorted and the maximum size grade ¼ to ⅛ mm. in diameter comprises 47 per cent of the total. The grade 1 to ½ mm. exhibits the greatest amount of abrasion with 59 per cent rounded and sub-rounded. In the channel deposits, the maximum size grade is in the diameter range of ½ to ¼ mm. Maximum abrasion is in the 1 to ½ mm. size with 50 per cent rounded and sub-rounded.

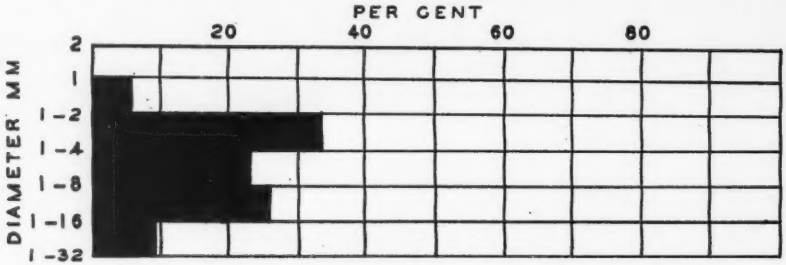


FIG. 2.—*Histogram of channel deposits at Dilia*

At Fort Sumner, the sorting of the sediments is better than at all points farther north along the river. The maximum size grade has a diameter range of ½ to ¼ mm. and varies in places from 49 to 67 per cent of the total. Quartz grains in the size grade ½ to ¼ mm. show the highest per cent of abrasion and vary from 40 to 50 per cent rounded and sub-rounded.

Downstream from Fort Sumner to Carlsbad, a distance of approximately 100 miles, there is little variation in the sediments. The maximum size grade has a diameter range of ½ to ¼ mm. and this grade comprises about 65 per cent of the total. The maximum abrasion is in the 1 to ½ mm. size with 25 to 50 per cent rounded and sub-rounded.

### HEAVY MINERALS

Magnetite: In the Pecos sediments this mineral is always associated with ilmenite. Commonly it occurs as irregular to rounded grains which are shiny black in reflected light and opaque in transmitted light. It may have characteristics which make it difficult to distinguish from ilmenite in which case its higher magnetism is a good criterion. About 75 per cent of the magnetite grains are found in the ⅛ to 1/16 mm. grade. The abundance of magnetite in respect to the total number of heavy minerals decreases from 43.7 per cent at Dilia to 22.5 per cent at Carlsbad.

Ilmenite: This mineral is very abundant in the ⅛ to 1/16 mm. grade, but rarely occurs in the larger grades. It commonly

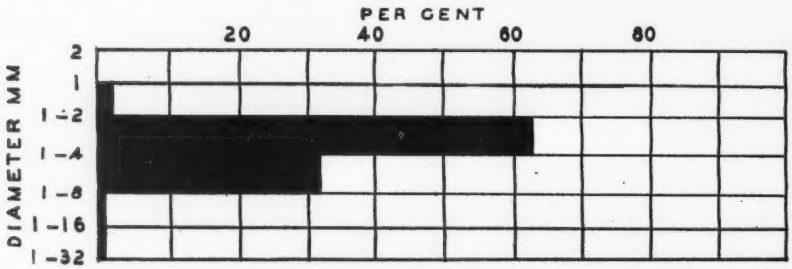


FIG. 3.—*Histogram of channel deposits at Carlsbad*

occurs as irregular, iron black to steel gray grains with a characteristic purple gray or sometimes crimson submetallic luster in reflected light. Grains are opaque in transmitted light. Partial alteration to leucoxene is frequently observed. Ilmenite decreases in abundance from 31.2 per cent in upper part of the stream to 12.2 per cent near the Texas border.

Garnet: This mineral is usually found as irregular, often fractured, sometimes well rounded grains. The pale pink variety is the most common, followed successively by dark red and yellow varieties. Yellow garnets are transported to the Pecos by tributaries from the Sierra Blanco Mountains. The pale pink grains may be confused with pink tourmaline. It is readily distinguished by its higher refractive index and its optically isotropic character. Garnets are most abundant in sediments with a diameter range of $\frac{1}{4}$ to $\frac{1}{8}$ mm. The per cent of decrease in abundance between Dilia and Roswell is from 3.8 to 1.9, but downstream from Roswell to Carlsbad this mineral increases to 10.8 per cent of the total.

Epidote: The majority of the epidote grains occur in the $\frac{1}{4}$ to $\frac{1}{8}$ mm. grade. The abundance of this mineral in respect to the total is from 5.2 per cent at Dilia to 12.4 per cent at Carlsbad. The common form of epidote in the Pecos is that of small angular to sub-rounded grains. The mineral is pale yellow to green in color.

Tourmaline: Five varieties, green, rose, black, brown, and blue, are represented in the Pecos sediments. This is a common mineral, and it is especially numerous in sands with a diameter range larger than $\frac{1}{8}$ mm. The most common variety is characterized by green, translucent, irregular grains whose form is largely determined by fracture and imperfect cleavage. Brown tourmaline has the same form as the green variety. Some of the green, black, and brown varieties occur as elongated prismatic grains which are often terminated by rhombohedral partings. Rose tourmaline is common and usually occurs in highly angular grains. The shapes are determined by fracture. The per cent in abundance of the five varieties listed increases downstream; green tourmaline from 2.8 to 10.8; rose tourmaline from 2.4 to 4.8; black tourmaline from 4.5 to 8.9; blue tourmaline from 0.2 to 1.2; and brown tourmaline from 0.1 to 3.0.

Hematite: The per cent of increase in abundance of hematite is from 2.5 at Dilia to 8.9 at Carlsbad. Hematite is found in all sizes and is most abundant in sands with a diameter range of $\frac{1}{4}$ to $\frac{1}{8}$ mm. This mineral is usually found as rounded earthy grains which are reddish brown in color in reflected light and opaque in transmitted light.

Rutile: In respect to the total number

TABLE 1. *Abundance in per cent of heavy minerals in respect to the total number at each locality*

| Mineral | | Dilia | Santa Rosa | Fort Sumner | Roswell | Artesia | Carlsbad |
|---|---|---|---|---|---|---|---|
| Magnetite | | 43.7 | 36.6 | 26.0 | 32.2 | 31.7 | 22.2 |
| Ilmenite | | 31.3 | 24.2 | 26.1 | 13.7 | 21.7 | 12.2 |
| Garnet | | 3.8 | 7.7 | 4.8 | 1.9 | 3.7 | 10.8 |
| Epidote | | 5.2 | 7.9 | 10.7 | 11.5 | 10.6 | 12.4 |
| Tourmaline | Green | 2.8 | 4.7 | 7.3 | 7.9 | 13.2 | 10.8 |
| | Rose | 2.4 | 3.2 | 4.9 | 3.2 | 3.6 | 4.8 |
| | Black | 4.5 | 7.5 | 8.9 | 8.9 | 3.6 | 8.9 |
| | Blue | .2 | .3 | .6 | .1 | 1.4 | 1.2 |
| | Brown | .1 | .1 | .2 | .6 | .9 | 3.0 |
| Hemitate | | 2.5 | 3.2 | 5.8 | 8.3 | 4.5 | 8.9 |
| Rutile | | .5 | .4 | .7 | 1.3 | .8 | 1.4 |
| Zircon | Trans. | 1.6 | 1.9 | 2.2 | 5.2 | 2.9 | 2.8 |
| | Purple | 1.5 | 1.8 | 2.3 | 5.2 | 1.2 | .4 |

of heavy minerals rutile is of minor importance. It is commonly found in the ⅛ to 1/16 mm. grade. It occurs as red, fractured, angular grains. The per cent of abundance of rutile increases from 0.5 at Dilia to 1.4 at Carlsbad.

Zircon: Zircon is the most common of the non-magnetic heavy minerals. The most prevalent type of grain is the colorless, prismatic form with pyramidal termination. Fractured grains are common, but highly angular grains are rare. Zircon nearly always exhibits a certain degree of rounding. The color ranges from colorless to purple. Most zircon particles are less than ⅛ mm. in diameter. The per cent of abundance of colorless zircon increases from 1.6 at Dilia to 5.2 at Roswell, then decreases to 2.8 at Carlsbad. The abundance of the purple variety exhibits a curve similar to the colorless type.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 85–91, FIGS. 1–2, TABLES 1–2, AUGUST, 1941

# HEAVY RESIDUES FROM SOME UPPER CRETACEOUS SEDIMENTS AT GINGIN, WESTERN AUSTRALIA

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ABSTRACT

The mineralogy of specimens of greensand, chalk, and sandstone from the Upper Cretaceous sediments at Gingin, 50 miles north of Perth, Western Australia are described. The heavy detrital minerals occurring in these sediments are: magnetite, ilmenite, leucoxene, zircon, tourmaline, rutile, kyanite, sillimanite, staurolite, andalusite, garnet, amphibole, epidote, zoisite, sphene, spinel, monazite, biotite, and anatase. This assemblage has been derived from the pre-Cambrian shield to the east of Gingin. The conditions of deposition of the greensands and chalk are discussed, and mechanical analyses of the greensands are given.

## INTRODUCTION

The township of Gingin (31° 21′ S. 115° 54′ E.) 50 miles north of Perth is situated almost at the southern extremity of an area of about 250 square miles of Cretaceous sediments consisting of a lenticular unit of chalk between two units of greensand. The chalk is Santonian in age (Withers, 1925). These Cretaceous sediments are underlain by micaceous sandstones and shales containing, in certain localities, plant remains which are possibly Jurassic. The lower greensand, varying in thickness from a few feet to almost 100 feet, immediately overlies the shales and sandstones, and is succeeded by 20 to 30 feet of chalk (the Gingin chalk) above which is the upper greensand at least 150 feet thick. These beds are practically horizontal, and their distribution is shown in figure 1, permission for the use of which was readily given by Mr. F. R. Feldtmann and Prof. E. de C. Clarke.

The mineralogy of the Gingin chalk has already been described in some detail (Carroll, 1939); this paper gives some information about the mineralogy and mechanical composition of the upper and lower greensands, the mineralogy of two additional specimens of chalk, and of a coarse-grained sandstone of the Cretaceous collected a few miles east of Gingin. The positions of these specimens, with the exception of the last-mentioned sandstone, are shown on figure 1. This paper deals particularly with the heavy detrital minerals and only passing reference is made to the "light" minerals including glauconite.

## HEAVY RESIDUES OF THE SEDIMENTS

A. *The Greensands.*—Two specimens of the upper greensand, no. 1 from Moorgup and no. 5 from Poison Hill (for positions see fig. 1), and one specimen of lower greensand (no. 6) from the quarry at Molecap, were examined. The specimens were easily disintegrated with a wooden pestle and mortar for the greensands are not compacted or cemented in any way. The material from each specimen was then sieved through a set of Tyler sieves with the results set out in table 1. From this table and from figure 2 it will be seen that the greensands are coarse, poorly sorted sediments.

The finest grades of material (the +125 and +250), were used for bromoform separation, and it was found necessary to remove the excess iron staining by boiling in a 1:1 conc. HCl solution. Both specimens of the upper greensand yielded very small quantities of heavy residue and no percentage figures were obtained. In the lower greensand, however, the +115 and +250 grades each yielded about 1 per cent of heavy residue,

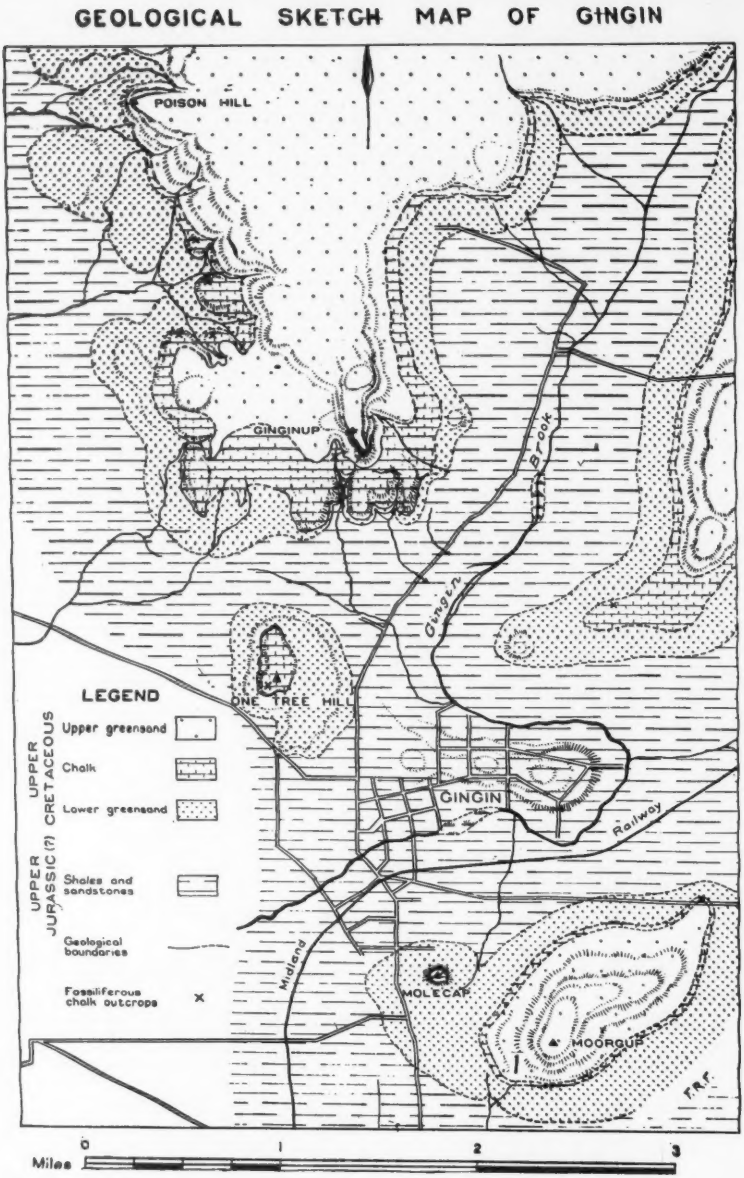


FIG. 1.—Geological sketch map of Gingin, south-western Australia, showing the positions of specimens described. (Compiled by F. R. Feldtmann from earlier maps and incorporating field-work recently completed by him.)

TABLE 1. *Mechanical analyses of upper and lower greensands*

| Screen openings mm. | Grade | Upper Greensand, No. 1, Moorgup | Upper Greensand, No. 5, Poison Hill | Lower Greensand, No. 6, Molecap quarry |
|---|---|---|---|---|
| | | % | % | % |
| 3.96 | + 5 | — | — | — |
| 1.98 | + 9 | 0.17 | 0.30 | 1.0 |
| 0.99 | + 16 | 11.05 | 13.94 | 6.46 |
| 0.49 | + 32 | 24.55 | 26.02 | 25.63 |
| 0.24 | + 60 | 31.65 | 36.02 | 37.02 |
| 0.12 | +115 | 18.84 | 15.21 | 22.93 |
| 0.06 | +250 | 8.55 | 5.02 | 4.46 |
| | −250 | 5.19 | 3.49 | 2.50 |

+ = retained on. Specimen numbers refer to position on map, figure 1.

two-thirds of which was found to be magnetic, the minerals removed being principally magnetite with a sprinkling of pink garnet.

The composition of these residues is shown in table 2 where it will be seen that there is much more variety in the mineralogy of the lower greensand than there is in the upper greensand. That the same minerals occur in both greensands is only to be expected, but there is not nearly such a large amount of heavy residue in the upper as there is in the lower greensand. The specimen of soil directly derived from the upper greensand (no. 2) gives a greater concentration of heavy minerals, produced by the weathering and soil forming processes than is obtainable with the samples of the upper greensand itself, for the soil results from the disintegration of several feet of greensand and, therefore, contains a larger proportion of resistant minerals than the small samples of greensand mechanically ana-

TABLE 2. *Heavy mineral assemblages of greensands, chalk, and sandstone*

| Specimen No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Magnetite | P | A | A | A | P | A | A |
| Ilmenite | A | A | A | A | A | A | A |
| Leucoxene | | + | + | + | | + | + |
| Zircon | + | + | + | + | + | + | + |
| Tourmaline | + | + | + | + | + | + | + |
| Rutile | + | + | + | + | + | + | + |
| Kyanite | + | + | + | + | + | + | + |
| Sillimanite | | | + | | + | + | + |
| Staurolite | + | + | + | + | | + | + |
| Andalusite | | + | + | + | | | + |
| Garnet | | | + | + | | + | + |
| Amphibole | | + | + | | | + | + |
| Epidote | | | + | + | | A | |
| Zoisite | | | | | | + | |
| Sphene | + | + | + | + | + | + | + |
| Spinel | | + | | + | + | | |
| Monazite | | | | | + | | |
| Biotite | | | | | | + | |
| Anatase | | | | | + | | |

A = Abundant; P = plentiful; + = present.

Specimen No. 1, Upper Greensand, Moorgup; 2, Upper Greensand soil, Ginginup; 3, Chalk soil, One Tree Hill; 4, Chalk, North Chalk; 5, Upper Greensand, Poison Hill; 6, Lower Greensand, Molecap quarry; 7, Sandstone, quarry about 4 miles east of Gingin. (Position of specimens is shown in fig 1.).

lyzed and used for this investigation.

The heavy mineral suite of the lower greensand consists of magnetite, ilmenite, leucoxene, zircon, tourmaline, rutile, kyanite, sillimanite, staurolite, sphene, epidote, amphibole, garnet, biotite, and zoisite. Apart from the opaque grains epidote is the most abundant of the remaining minerals, followed by zircon, garnet, kyanite and tourmaline. The grains are generally robust and chunky, the majority being quite fresh and unworn. The characteristic distinguishing features of the suite are the association of purple zircon with epidote, pink garnet, and kyanite. Purple zircon grains are striking on account of their deep color, and the darkest are pleochroic from a warm brownish purple to a yellowish brown. Many of these grains are rounded, some are zoned, and most contain inclusions. The origin of the purple zircon will be discussed when considering the provenance of the entire suites of the Cretaceous sediments so far examined.

As shown in table 2 the upper greensand, although containing many of the same minerals as the lower greensand, has a much more restricted suite, but both specimens, and also the soil, yielded spinel, andalusite, and in one specimen only, monazite, which appear to be absent from the lower greensand. Garnet does not form a part of the upper greensand suites, but kyanite is conspicious. Epidote is also present. The heavy mineral grains from the upper greensand are smaller and more worn than those of the lower greensand, and it would appear that erosion of the land surface which contributed the material was less active than in lower greensand times. There is a possibility too, that some of the lower greensand material was re-worked into that of the upper greensand as the mechanical analyses are almost identical,

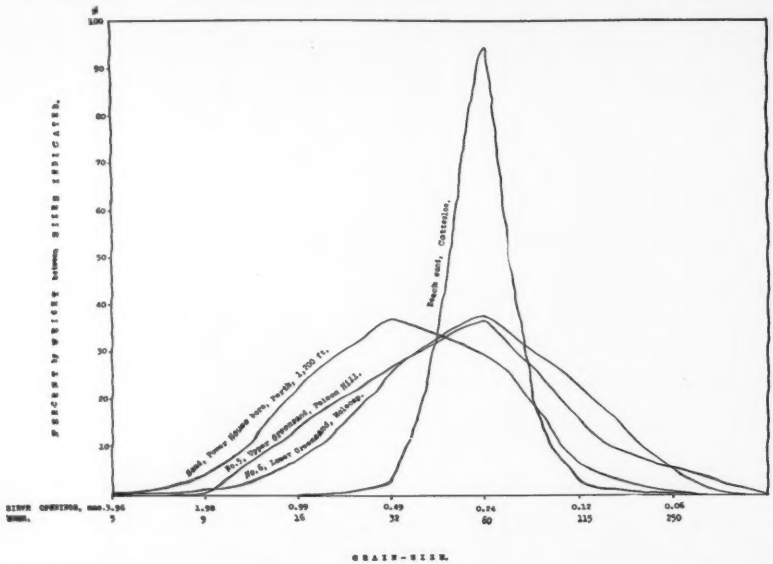


FIG. 2.—Mechanical analyses of upper and lower greensands. Analyses of a beach sand and of a sand from a boring at Perth are added for comparison.

and yet there are few heavy minerals.

B. *Chalk.*—The chalk is represented by two specimens, no. 3, a soil directly derived from the chalk at One Tree Hill; and no. 4, a glauconitic chalk from the locality known as North Chalk (positions shown on fig. 1). The chalk soil (no. 3) is a black clayey soil with numerous fragments of chalk. The clay fraction was washed out as much as possible and the residue treated with acid to remove the carbonate. The chalk at One Tree Hill is a fine-grained, white rock strongly resembling the English chalks and it contains very little sand or glauconite. The One Tree Hill chalk is similar to that previously described from Molecap (Carroll, 1939), but the chalk at North Chalk contains abundant glauconite and rather large quartz grains, many of which are well-rounded. The chalk bed thins out to the north and disappears north of Poison Hill. The specimen from North Chalk (no. 4) appears to be on the margin of the area in which chalk deposition took place, whereas the specimens from One Tree Hill and Molecap are from near the center of this deposition area.

Both specimens carry a large suite of heavy minerals, many of which are identical with those of the lower greensand, but there are several important differences; first, the zircon is to a large extent colorless and the purple variety is inconspicuous in amount; secondly, garnet is also colorless, and not the strong pinkish brown grains that are so characteristic of the lower greensand; thirdly, pale green spinel is present in both the chalk samples; fourthly, kyanite is very conspicuous and is often a pale washy blue in color and slightly pleochroic. These differences in heavy minerals are sufficient to show that by the time the chalk was being deposited, different rocks were being eroded from those exposed in lower greensand times.

This easily recognizable suite of minerals is present in the presumably Tertiary sediments, and soils derived therefrom, some miles to the west of Gingin, indicating that the erosion of the Cretaceous has been considerable.

C. *Sandstone.*—A coarse-grained, incoherent, sandstone (no. 7) was collected from a quarry about four miles east of Gingin, and therefore nearer to the pre-Cambrian complex. No mechanical analysis was made but the coarsest material, consisting almost entirely of quartz, was removed by sieving, leaving only a few grams of fine sand which, on separation, yielded an appreciable quantity of heavy residue, about one-sixth of which was magnetite. The assemblage (see table 2) is rather similar to that of the lower greensand as it contains abundant purple zircon in worn and fresh grains, but it lacks the epidote of the greensand, and garnet is present only in small amounts. The general appearance of the minerals is rather less angular than those of the lower greensand, but is not unlike that of the upper greensand. In fact, it is possible to consider this sandstone as an in-shore facies of the upper greensand which was deposited under conditions not conducive to the formation of glauconite.

## SIGNIFICANCE OF HEAVY MINERAL RESIDUES

The lower greensand was laid down on an old undulating land surface of shales, probably Jurassic, which has been exposed (see fig. 1) by erosion. The Jurassic shales containing plant remains in places are considered to be of fresh water origin. A new series of sediments of marine deposition began with the lower greensand, the heavy minerals of which are fresh and unweathered. The assemblage contains many minerals, replicas of which can be obtained in a belt of pre-Cambrian country known as the Chittering Valley which runs north and south some miles to the east of Gingin. The rocks outcropping there include garnet-, staurolite-, sillimanite- and kyanite-schists, gneisses, and some bands of greenstone. Garnet, kyanite, sillimanite, and staurolite in the lower greensand assemblage undoubtedly came from these rocks, as did purple zir-

con, an accessory in some of the gneisses, and pale green spinel (Simpson, 1937). Amphibole and epidote must have been contributed by the greenstones.

The fact that the quantity of heavy minerals decreases in the upper greensand and that there is very little clay in the Cretaceous suggests that conditions along the Australian coast were similar in Cretaceous times to those of the present day, i.e., long stretches of coast-line, rather low lying and with very few rivers. There is at present not much material being deposited in the Indian Ocean off Western Australia as shown by the amount of material carried by rivers (Carroll and Clarke 1940). Glauconite now occurs off the west and south coasts of Australia where it forms a continuous belt between 50 and 400 fathoms (Jukes-Brown, 1900, p. 417).

Although this paper is only incidentally concerned with glauconite, it would be incomplete without considering it to a certain extent, for it makes up a large part of the greensands, and indicates definite conditions of deposition. According to Galliher (1935), glauconite occurs, with rare exceptions in close association with areas of quiet black muds and sands, i.e. in an anaerobic environment. Evidence of this is present at Gingin in the abundant pyrite in certain parts of the upper greensand at Poison Hill (near where specimen five was collected). Glauconite takes a long time to form, hence sedimentation must have been slow; while glauconite is forming the surface of deposition must not be covered by other sediments, or the process ceases. Galliher has stated (1939) that glauconite develops principally from biotite, and certainly odd grains of biotite do occur in the lower greensand; Takahashi (1939), from a study of Japanese glauconites, considers that "the mother materials of glauconite seem to be substances that are gelatinized before being transformed into glauconite" and hence it can possibly develop from clays. A summer temperature of not lower than 15°C and a salinity not less than normal sea water seem necessary for glauconitization. The minimum average summer temperature for this part of Australia (taking the averages for Perth) is 16.3°C.

The coarseness and lack of sorting (see fig. 2) of the greensands indicate that shallow water, or continental shelf conditions, probably prevailed, for coarse sand very generally occurs at present at a depth of about 20 fathoms off the coast of Western Australia (Admiralty Chart, no. 1033). The poor sorting shows that no strong currents prevailed at that time.

The thickness of the greensands (mentioned above) indicates that during deposition, the area sank very slowly. The lenticular nature of the chalk suggests that the the time of its deposition there may have been no movement and that the chalk tended to fill in the deeper parts of the sea-floor. That some terrigenous material was added at that time is shown by the rather distinctive though scanty detrital minerals described from the chalk specimens so far examined. The slow sinking which again took place during upper greensand times may have caused the erosion of a land surface to the east of the Chittering Valley. It is considered that the lower greensand detritals are derived from the rocks of the Chittering Valley, whereas, those of the upper greensand are not so definitely derived from the same source.

Although deposition of the greensands was probably slow and in rather still water conditions, the rounding of the quartz grains indicates that they had been subjected to a considerable amount of abrasion prior to their incorporation in the greensands. This wear took place in water and may have occurred at or near a beach.

ACKNOWLEDGMENTS

This investigation formed part of the research program in the University of Western Australia initiated by the Commonwealth Research Grant which is hereby gratefully acknowledged.

My thanks are due to Prof. E. de C. Clarke and Mr. F. R. Feldtman for many helpful discussions.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 92–93, FIG. 1, AUGUST, 1941

# TRANSPORTATION OF ROCK PARTICLES BY SEA-MAMMALS*

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ABSTRACT

Gastroliths, sometimes in large quantities, have been found in the stomachs of many sea-mammals. Although the animals are not of great importance as agents of transportation, they provide an interesting demonstrated means of pebble rafting.

In the geological literature, there are a few references regarding the efficacy of sea mammals in distributing pebbles carried as stomach stones. The source material quoted, however, has been no more recent than the reports of the Challenger Expedition (Murray and Renard 1891), although later data are available.

Stones have been found in the stomachs of the California sea lion, the Steller's sea lion, the sea elephant, the fur seal, the Peruvian seal, the harbor seal, and the Walrus (Scammon, 1874; Turner, 1887; Jordan, 1898; Johansen, 1912; Howell, 1930; Schroeder and Wegeforth, 1935; C. R. Schroeder, C. M. Hermann, G. E. MacGinitie, personal communications). Single rocks weighing as much as five pounds and aggregates of 25 pounds are mentioned. Apparently none of the pebbles were carried long enough to become highly polished like the gastroliths of dinosaurs (Wieland, 1907).

The writer has examined the stomachs of 11 dead sea lions which had drifted up on beaches near La Jolla, California. Although most of these stomachs were completely empty, one contained a single flat pebble of sandstone, and another had the pebbles shown in figure 1. Twenty-three of these rocks are wave-rounded Black Mountain metavolcanics, the other four are fragments of shale probably of Eocene or Cretaceous age. All of these types of rock are available on beaches near La Jolla. Because of the angularity and fragileness of the shale, it seems likely that the stones had not been carried very long by the sea lion, although some of the metamorphics seem to be very slightly polished.

Formerly the stones were thought to serve as a ballast to aid in diving (Murray and Renard, 1891). Later it was suggested that they might serve as a sort of "gastric chewing gum" to prevent atrophy of the male's stomach during the long period of fasting in the mating season (Howell, 1930). A function of crushing worms which frequently infest stomachs or of rubbing ulcers has also been proposed. More recent work, however, seems to check Turner's conclusion (1887) that the pebbles are used to triturate food (Schroeder and Wegeforth, 1935; C. M. Hermann personal communication). Schroeder has also noted that large numbers of pebbles are removed from the floor of zoo tanks by sea lions and seals soon after feeding, and a few hours later they reappear in their former abundance on the tank floor, apparently having been regurgitated after the food had been digested.

Although it is certain that some sea mammals are a factor in the distribution of pebbles on the sea floor, they cannot be quantitatively important as geological agents. On the other hand, it should be borne in mind that the presence of infrequent pebbles in fine-grained sediments may sometimes be due to the activity of sea mammals as well as to other forms of rafting.

* Contributions from the Scripps Institution of Oceanography, New Series, No. 139.

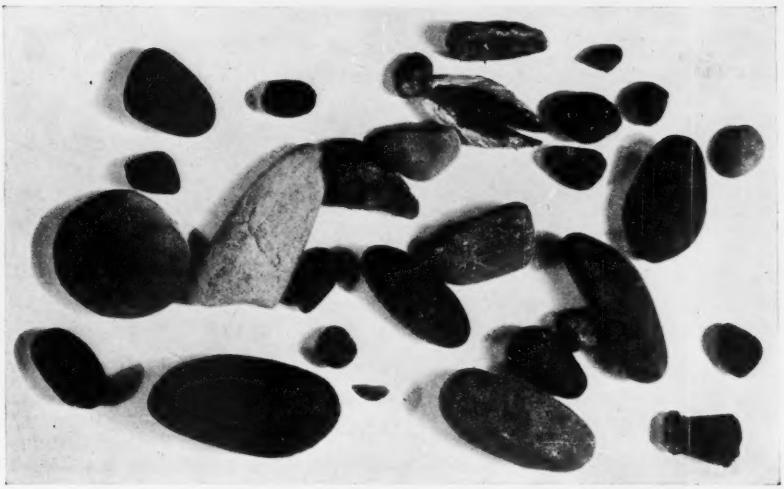

FIG. 1.—Pebbles removed from stomach of female sea lion at La Jolla, California. Rounded dark pebbles are Triassic Black Mountain meta-volcanics; lighter flat fragments are Eocene or Cretaceous shale. Note the single mussel shell. (×½)

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 94–97, FIGS. 1–4, AUGUST, 1941

# PROJECTION SPHERICITY

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## ABSTRACT

The study of the shapes (sphericity) of sedimentary particles has been handicapped by the confusion from the great number of shape measures, and the time-consuming methods. The present paper attempts to show the relation between the various two dimensional shape measures, and introduces a rapid method especially adaptable to particles of the sand-size.

All sphericity measurements may be divided into two general classes; those depending on individual particle measurements, and those depending on grain aggregate measurements. Because aggregate measurements give only a mean sphericity and tell nothing about the sphericity distribution, our concern is with individual particle measurements. These may again be divided into two classes: three dimensional methods, and two dimensional or projection methods. This paper is devoted only to projection methods because projection methods must be used in examining microscopic fragments.

Pentland (1927), Cox (1927), Tickell (1931), and Wadell (1935) have studied projection sphericity. Pentland, Cox, and Tickell, however, called their measures "roundness." The formulae they have developed are as follows:[1]

Pentland $\phi_p = \dfrac{A}{A_d}$

Cox $\phi_c = \dfrac{4\pi A}{P^2}$

Tickell $\phi_t = \dfrac{A}{A_c}$

Wadell $\phi_w = \dfrac{d_c}{D_c}$

All the above methods involve:

1. The tracing or photographing of the enlarged image of the grain.
2. Planimetric measurement of the area of the grain, and in the case of Cox's method, measurement of the perimeter.
3. Measurement of the long diameter or area of the circumscribing circle.
4. Calculation of the sphericity from these data.

This has been so time consuming that very few workers have had the energy to undertake detailed studies.

The method proposed in this paper involves only the square root of the ratio of the inscribed and circumscribed circles (fig. 1) and is called the inscribed circle sphericity.

$$\phi_0 = \sqrt{\frac{i}{D_c}}.$$

$A$ = cross-sectional or projection area of the grain
$A_d$ = area of a circle having the same diameter as the long diameter of the grain
$A_c$ = area of the smallest circumscribing circle
$P$ = perimeter of the grain
$d_c$ = nominal sectional diameter; the diameter of a circle having the same area as the grain
$D_c$ = diameter of the smallest circumscribing circle

[1] Pentland and Cox did not specify any definite orientation of the grains; Tickell specifies a random orientation; Wadell's work and the work in the present paper are based on measurements in the maximum cross-sectional area, i.e., the cross-section containing the long and intermediate diameters.

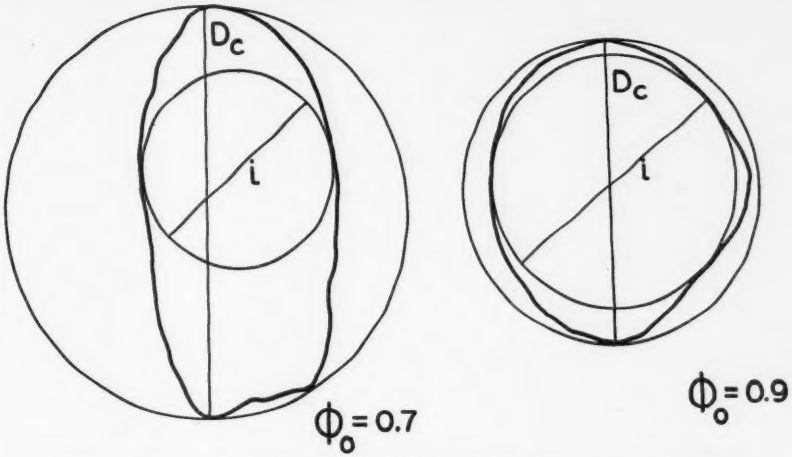


FIG. 1.—The inscribed and circumscribed circles of the maximum cross-sectional area.

A concentric circle protractor, (fig. 2), such as proposed by Wadell for the measurement of the roundness of particles, is used to measure "$i$", the inscribed circle diameter, "$D_c$," the circumscribing circle diameter. $\phi_0$ can then be obtained from one setting of a slide rule.

Wadell's protractor has been adapted to fit the ocular of a microscope in place of the cross hairs, so that rapid measurements can be made on very small particles. The use of a mechanical stage also facilitates the measurements. No projection drawings, no planimetric measurements, and no calculations other than one slide rule setting are needed. Roundness measures and size measurements can be made at the same time, the protractor-ocular again eliminating the projection drawings.

An important feature that must be emphasized is that Wadell's methods are theoretically sound, and therefore can be used in quantitative studies. The validity of other sphericity measures is dependent upon correlation with Wadell's sphericity. Figure 3 shows the histogram, mean, standard deviation, and the median for three different particulate systems based on Wadell's projection sphericity and the inscribed circle sphericity. Although the histograms themselves are dissimilar, their parameters are well within the limits of error of measurement. The average coefficient of correlation for the three examples is 0.94, which means that statistically $\phi_0$ is equal to $\phi_w$. This can be demonstrated geometrically by plotting $\phi_0$ against $\phi_w$. For elliptical cross-sections $\phi_0 = \phi_w$. The deviations from equality for rectangles and isosceles triangles is small and is shown in figure 4.

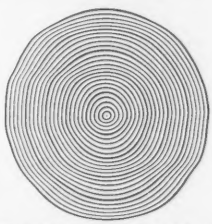

FIG. 2.—Wadell's concentric circle protractor.

Because $\phi_0 = \phi_w$, and an area is proportional to the square of the diameter, the following is statistically valid.

$$\phi_0 = \phi_w = \phi_p^{1/2} = \phi_i^{1/2} \sim \phi_c^{1/2}.$$

Alling (1941), using a diaphragm in a

microscope system, describes a method for determining the nominal sectional diameter. His method is applicable to grains mounted so the maximum cross-sectional area is measured (Wadell, 1935), but is not applicable to thin section analysis. This is true because in a thin section, the apparent size and shape of a particle is a

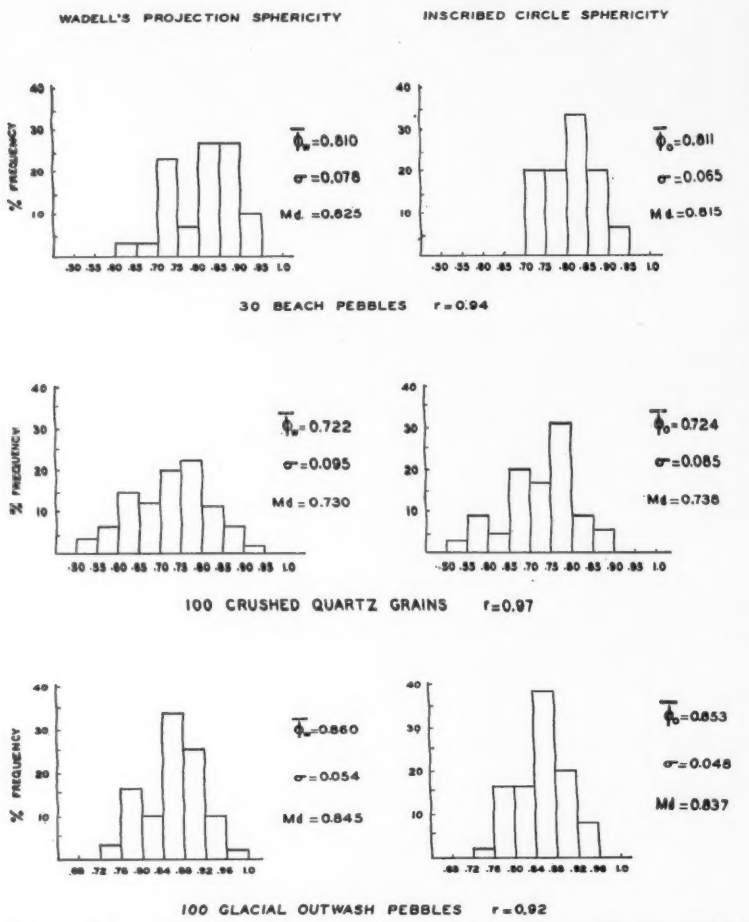


FIG. 3.—Histogram distribution of three different particulate systems by Wadell's projection sphericity and the inscribed circle sphericity. $\bar{\phi}$=mean sphericity; $\sigma$=standard deviation; *Md*=median; *r*=coefficient of correlation.

function of its volume, true shape, orientation, and position of the section. However, in the case of mineral grains mounted so the maximum cross-sectional area is measured, it was shown that $\phi_w = d_c/D_c = \sqrt{i}/D_c = \phi_0$ or $d_c = \sqrt{iD_c}/M$, where $M$ is the magnification. Therefore, $d_c$ can be rapidly calculated from the shape data.

The inscribed circle method can be used to find the shape and nominal sectional diameter of mineral grains under the microscope or from the projection of mineral grains on a screen by a microprojector.

The writer thanks Drs. F. J. Pettijohn and W. C. Krumbein for helpful suggestions and criticisms.

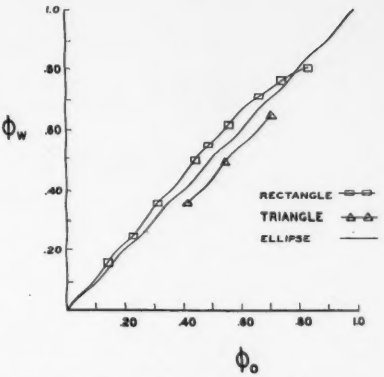


FIG. 4.—Comparison of $\phi_0$ and $\phi_w$ for rectangles, isosceles triangles, and ellipses.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 2, PP. 98–101, FIGS. 1–2, TABLE 1, AUGUST, 1941

# LOCAL AREAL VARIATION OF HEAVY MINERALS IN BEACH SAND

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*ABSTRACT*

Twenty-four samples of beach sand were collected on a grid pattern along the southern shore of Lake Michigan, and were analyzed for their heavy mineral content. The per cent of heavy minerals by weight was plotted on a map for each sample site and contours were drawn through points of equal weight per cent. The contours parallel the shore and the weights decrease waterward, suggesting that the trend of old shorelines and possibly even the strand line itself may be determined by heavy mineral weight studies of ancient lake and marine marginal sands.

## INTRODUCTION

In 1938 Krumbein and Griffith stated as a principle that the contours of sediment characteristics along a beach tend to parallel the shoreline. This was based on a size and shape study of cobbles and pebbles from the beach environment of Little Sister Bay, Wisconsin. Krumbein extended the principle (1938) to the sand sizes with a study of the areal variation of the average grain size of twenty-four samples from Waverly beach, on the southern shore of Lake Michigan about 10 miles west of Michigan City, Indiana. The geometric mean diameters were contoured as an elongate trough with the major axis paralleling the shore; interruptions of the linear trend were attributed to tongues of coarser material carried in by storm waves. The present author made a heavy mineral study of the same set of samples and found an even more emphactic verification of the linear trend.[1]

## METHOD OF ANALYSIS

The beach was sampled as shown in figure 1, with 3 rows of 8 samples each, 60 feet apart along the beach, each row being 30 feet from the next across the beach. Approximately 100 grams were split from each field sample for heavy mineral study. Each split was sieved into grades corresponding to the $\sqrt{2}$ modification of the Wentworth scale (Krumbein and Pettijohn, *1938*, pp. *80, 137*) but only the sizes 0.246–0.175 mm. and 0.175–0.124 mm., convenient for heavy mineral study, were used. The heavy minerals were separated from each frac-

[1] The complete study was presented by the author as a Master's thesis to the University of Chicago, 1939 (see bibliography at end of this paper). Part of the results were published jointly by Krumbein and the author (1940).

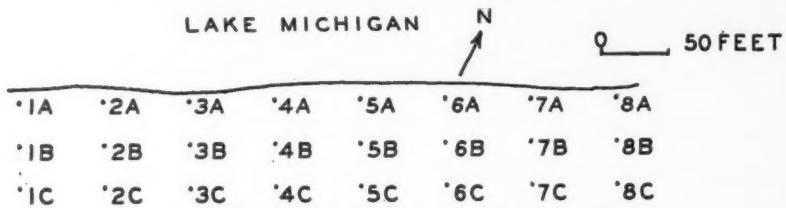


FIG. 1.—Map showing location and number of samples.

tion by flotation in bromoform (sp. g. =2.85), and weighed. These weights were expressed both as a per cent of the total sample weight and as a per cent of the size grade. Both sets of data yielded good contour maps, but the maps of per cent of size grade were slightly better because the heavy minerals constitute a larger proportion of the size grade than of the whole sample. Only the values for per cent of size grade are included in this paper. Weight percentages of each of the two grade sizes were contoured separately and the total heavy mineral weight, taken as a per cent of the combined size fraction weights, was also contoured (see figure 2). The fact that an improved linear map was obtained suggests that random fluctuations of the smaller samples were largely eliminated by the combined data. The observed data for the two size grades and the combined grades are given in table 1.

INTERPRETATION OF THE DATA

Figure 2 shows the data of table 1 plotted to scale on maps, each heavy mineral weight percentage placed at its corresponding sampling point. Contours were drawn through equal values using an interval dependent upon the range of values in each map. It was believed that relatively few lines would indicate the pattern, whereas too small an interval would introduce a spurious accuracy into the data. Comparison of the upper two drawings shows a rough linearity with a rough correspondency of higher heavy mineral concentrations in the 2nd and 4th columns, and between the 7th and 8th columns, with lower concentrations in the 1st, 5th and 6th columns. The third column is indeterminable because of the anomalous sample, #3a, of the larger grade size. The combined data of the lower figure yield a smoother set of contours.

TABLE 1. *Heavy mineral content of beach sand*

| Sample | 0.175–0.124 mm. | | 0.246–0.175 mm. | | 0.246–0.124 mm. |
|---|---|---|---|---|---|
| | Weight of Heavies (gm.) | Per cent of Heavies in Size Grade | Weight of Heavies (gm.) | Per cent of Heavies in Size Grade | Combined per cent of Heavies in Size Grade |
| 1A | .06 | 2.2 | .06 | .25 | .45 |
| 1B | .20 | 3.7 | .09 | .34 | .91 |
| 1C | .36 | 5.3 | .24 | .50 | 1.09 |
| 2A | .07 | 2.4 | .06 | .24 | .47 |
| 2B | .29 | 5.3 | .19 | .60 | 1.29 |
| 2C | .26 | 6.0 | .21 | .64 | 1.27 |
| 3A | .12 | 3.7 | .20 | .70 | 1.01 |
| 3B | .25 | 4.0 | .19 | .48 | .96 |
| 3C | .42 | 6.7 | .26 | .71 | 1.59 |
| 4A | .17 | 3.5 | .12 | .37 | .77 |
| 4B | .39 | 5.1 | .27 | .56 | 1.19 |
| 4C | .30 | 7.1 | .21 | .65 | 1.40 |
| 5A | .15 | 2.4 | .13 | .35 | .65 |
| 5B | .30 | 3.8 | .21 | .44 | .91 |
| 5C | .33 | 6.4 | .23 | .70 | 1.48 |
| 6A | .23 | 3.0 | .13 | .34 | .79 |
| 6B | .25 | 2.7 | .18 | .40 | .79 |
| 6C | .31 | 6.8 | .20 | .67 | 1.48 |
| 7A | .15 | 3.9 | .12 | .37 | .75 |
| 7B | .30 | 3.8 | .20 | .48 | 1.00 |
| 7C | .29 | 4.8 | .21 | .61 | 1.24 |
| 8A | .03 | 1.9 | .03 | .19 | .34 |
| 8B | .31 | 4.8 | .14 | .40 | 1.09 |
| 8C | .32 | 7.5 | .20 | .57 | 1.32 |

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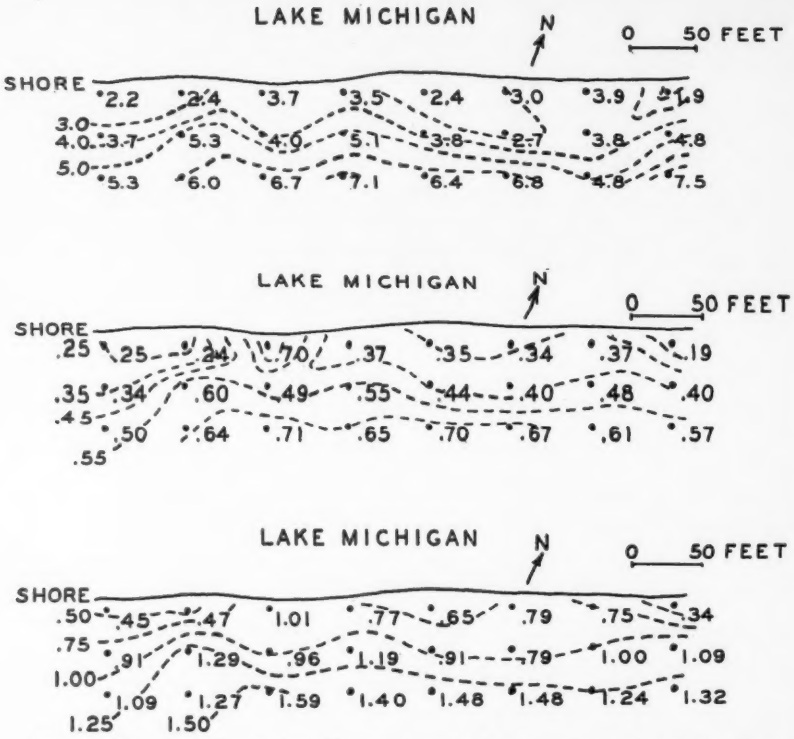


FIG. 2.—Maps of areal variation of heavy mineral weight percentages of grade size. Upper figure, 0.175–0.124 mm., middle figure, 0.246–0.175 mm., lower figure, combined data from 0.246–0.124 mm.

An explanation of the greater percentage of heavy minerals on the upper part of the beach may be attempted by consideration of heavy mineral densities. Because of its greater density a heavy mineral particle has a settling velocity equal to that of a larger particle of quartz or feldspar (the predominant constituents of the beach sand). The speed of an incoming wave diminishes rapidly as it rushes upon a shallowing beach so that for any given mass there is a certain point at which all particles of that weight settle out (neglecting shape and surface area, which are important, but are not contradictory to the simplified picture given here). The magnitude of velocity of the water returning on the ebb is much less because of friction losses, and because of volume loss in sinking into the sand. Therefore for any given point the water can move only particles of somewhat smaller settling coefficient than it deposited on its inflow. Thus it will remove quartz and feldspar of a given size on the return more easily than heavy minerals of that size. Consequently there may be a greater percentage of heavy minerals of a given size on the higher reaches of the beach than on the lower.

The heavy minerals were also mounted

on slides and identified under the microscope. The number percentages of the predominant heavy minerals in each of the two size grades and in the combined size grade were plotted on maps, but they all yielded random variation patterns with contours that showed no trends. Ratios of one heavy mineral against another or against the total heavy mineral weights also yielded random patterns. The ratios were suggested by Pettijohn's (1931) study of Lake Michigan beach sands, in which he found that the ratios of various heavy minerals to garnet were more significant than the percentages directly, because garnet is practically indestructible. For his study the ratios were undoubtedly useful, but here, where only 420 feet of beach is involved, abrasion is negligible with respect to selective transportation.

One may say that linear patterns may be the rule in heavy mineral weight variations along beaches. If further studies prove them to be the rule, then the trend of old shorelines can be ascertained by heavy mineral studies of old beach sandstones. The next step would be to determine how the heavy mineral weights vary perpendicular to the strike of the shore, that is waterward. In this study they were found to decrease, although not enough area was sampled to determine if the decrease was regular; or if so, whether it is linear, hyperbolic, or exponential. Furthermore there are no data on the pattern of the weight percentages under water, away from the shore. Whether the heavy minerals decrease to a small value or remain constant or whether they increase again, is not known. Answers to these questions may enable sedimentary petrologists to determine not only the direction of old shorelines but their seaward edge also. Purely as an hypothesis one may anticipate that the percentages rise in the zone where the sand grades into the silt, on the ground that heavy minerals appear to be generally associated with finer sizes.

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## REVIEW

ROLLIN ECKIS and P. L. K. GROSS, Geology and Ground Water Storage Capacity of Valley Fill: *State of California, Dept. of Public Works, Division of Water Resources, Bull.* 45, 1934. Pp. 279, with many figures and maps

The reviewer believes that this bulletin, although published several years ago, should be called to the attention of sedimentary petrologists. It represents a thoroughgoing study of ground water conditions in southern California, and it is noteworthy for its complete set of mechanical analyses of alluvial fan deposits. An appendix at the end of the volume includes these data on 241 analyzed samples, giving the complete percentage compositions, as well as the mean size, the size ratio deviation (Wentworth), and the porosity and specific yield of the deposits.

The bulletin begins with the general geology of the south coastal basins (San Fernando, San Gabriel, Upper Santa Ana, and Coastal Plain basins) of California. The sediments which produce fresh water in these basins are then described in detail, with consideration given to such items as their weathering, compaction, and cementation. Graphs are included, for instance, showing the relation of the porosity of the sediments to their depth of burial. A detailed discussion of each basin follows, with emphasis on the ground water features. Scattered through these descriptions are interesting discussions of the properties of the sediments as functions of their areal distribution on the fans.

Sedimentary petrologists will find the two appendices at the end of the volume particularly stimulating. The first (about 30 pages) discusses theoretical and experimental considerations of the water-yielding capacity of the sediments. Porosity and specific retention are discussed in some detail, and the authors demonstrate certain relations between these properties of the sediments and the size parameters. For example, a graph is shown of the relation between porosity and the ratio deviation ("sorting") of the sediments, based on 201 samples. The relation is approximately linear, and indicates that porosity diminishes as sorting becomes poorer. The full mechanical analysis data on which such graphs are based is given in tabular form in a second appendix. The analyses are based on Wentworth grades, expressed as weight percentages. Below each tabulation are three statistical parameters—the mean size in mm., the ratio deviation, and a surface factor. These values are supplemented by the experimentally determined porosity, retention, and specific yield of each sample.

The bulletin is a useful reference for typical examples of alluvial sands and gravels, and affords a basis for generalized descriptions and comparisons of such sediments. The samples represent a wide variety of depositional conditions, and the data are valuable for studies of the broad areal variations in sedimentary characteristics on alluvial fans. The authors themselves give data on the median size of boulders along the cones at the base of the San Gabriel Mountains. For example, at the apex of the fan at Lytle Canyon the median boulder size is 87 inches; 2.5 miles downstream it is 54 inches; and 5 miles downstream it is 30 inches. Thus, within about 3.5 miles from the mouths of the canyons the boulders apparently decrease to half their previous size. Such studies have an interesting bearing on the question of particle wear vs. selective transportation.

The bulletin is well organized and clearly written. It should be available in the library of every sedimentary petrologist.

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